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Project Report

ATC-103

Active BCAS: Design and Validation of the Surveillance Subsystem

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17 December 1980

Prepared for the Federal Aviation Administration by

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16. Abstract

Lincoln Laboratory, under FAA sponsorship, is developing an Active Beacon Collision Avoidance System (BCAS), concentrating primarily on the air-to-air surveillance subsystem. The surveillance functions required are to detect the presence of nearby aircraft (whether they are equipped with ATCRBS transponders or DABS transponders), and then generate a surveillance track on each aircraft, issuing range and altitude reports once per second.

The development effort consisted of airborne measurements complemented by simulation studies and analyses. The basic effects of ground-bounce multipath, interference, and power fading were assessed by air-to-air measurements. In other measurements, the BCAS interrogation and reply signal formats were transmitted between aircraft, and the results recorded for later playback and computer processing using the BCAS surveillance algorithms. This is a flexible means of experimentation which allows many of the design parameters to be changed as the effects are noted. In the most recent phase of the program, Lincoln designed and built realtime BCAS Experimental Units (BEUs), flight tested them, and then delivered them to the FAA for more extensive flight testing. In one of these flight tests, a BEU-equipped Boeing 727 flew to New York, Atlanta, and other major terminal areas in the eastern U.S. An analysis of BEU performance during this "Eastern Tour" is given in this report.

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1. INTRODUCTION

An Active Beacon Collision Avoidance System (BCAS) is being developed at M.I.T. Lincoln Laboratory for the Federal Aviation Administration (FAA). Active BCAS equipment on board an aircraft detects the presence of other nearby aircraft, and uses this information to display a warning to the pilot when necessary. More specifically, the Active BCAS unit provides surveillance information on all nearby aircraft equipped with transponders and encoding altimeters, determines if any of these aircraft represent collision threats, if so selects an appropriate maneuver, coordinates the maneuver with other aircraft and then displays an advisory to the pilot. The beacon carried by another aircraft that makes this surveillance possible is simply an ATC (Air Traffic Control) transponder. This can be either an ATCRBS (Air Traffic Control Radar Beacon System) transponder or a DABS (Discrete Address Beacon System) transponder. The concept and basic operating principles of Active BCAS are described more fully in Ref. 1. The Lincoln effort is focused principally upon the DABS-mode and ATCRBS-mode surveillance functions of Active BCAS. New techniques have been developed for air-to-air interrogation, for overcoming the effects of ground bounce multipath and signal interference, and for processing transponder replies to form tracks.

The initial design and validation was carried out using an airborne experimental testbed which provided detailed reply pulse data tape recorded for later time processing on the ground. In subsequent phases of the program, real time BCAS Experimental Units (BEU) with pilot displays were designed, constructed, and then evaluated in a variety of aircraft including typical air carrier aircraft, engaged in typical flight operations.

This report presents the results of key experiments and the initial operational flight tests. Section 2 describes the general approach and experimental facilities. Section 3 provides a summary of basic air-to-air link data and a description of the analysis and measurement data used to validate each of the various surveillance techniques. An assessment of overall surveillance performance as measured during recent flight tests at several major cities in the eastern United States is given in Section 4.

2. METHODOLOGY

The design and validation of the Active BCAS surveillance function at Lincoln Laboratory has made use of several complementary development techniques:

- Basic measurements of the characteristics of the air-to-air radio link
- Computer simulation using modeled data
- Non-real time simulation using test measurements obtained during instrumented flight
- Real-time systems in flight test

The development of the DABS mode surveillance function also took advantage of extensive knowledge accumulated at Lincoln Laboratory during the development of the DABS ground-to-air link. Computer models provided a means to conduct Monte Carlo trials of the BCAS DABS surveillance algorithms as they were developed and refined. See Fig. 2-1.

The basic link measurements and the non-real-time simulations using real data were made possible by the existence of an instrumented aircraft referred to as the Airborne Measurement Facility (AMF). The AMF was originally used by Lincoln Laboratory as a means of recording RF pulse data received on either of the two beacon frequencies (1030 MHz uplink, 1090 MHz downlink).

The AMF consists of two subsystems as indicated in Fig. 2-2. The airborne subsystem provides for the reception of signals in the selected band, conversion to digital data samples, and storage on instrumentation-type magnetic tape along with data representing aircraft state and position. The ground subsystem includes a means for playing back the recorded data, a computer for editing and reformating, and a tape transport to transcribe the data to general purpose computer tape. The AMF installed in a Piper Navajo aircraft is shown in Fig. 2-3. A more detailed specification of the AMF is given in Ref. 2.

During the BCAS program the AMF was modified to include a transmitter and DABS reply detector. Flight tests were conducted using the AMF on a Cessna 421B and a DABS transponder on a Beech Bonanza. An extensive data base covering various encounter geometries and multipath conditions was acquired and used as a data source for the DABS mode simulation trials, Fig. 2-1. As illustrated in the figure, pure simulations were also conducted through the use of a DABS reply model. Here DABS replies were generated from an adjustable scenario involving a hypothetical DABS-equipped aircraft. Appendix A contains a more detailed description the AMF as it was configured for the BCAS development.

The AMF also provided a reply pulse data base during a series of encounters with aircraft carrying conventional ATCRBS transponders. The pulse data was processed using a computer model of candidate ATCRBS Reply Processors. The resultant replies were then provided to the ATCRBS surveillance algorithm to produce track data. This processing sequence is shown in Fig. 2-4.

Later when real time BCAS Experimental Units (BEU) were built, provisions for recording data at the reply level allowed evaluation, modification, and refinement of the ATCRBS surveillance algorithms using software resident in the Software Development Facility that is identical to the real-time software (Fig. 2-4).

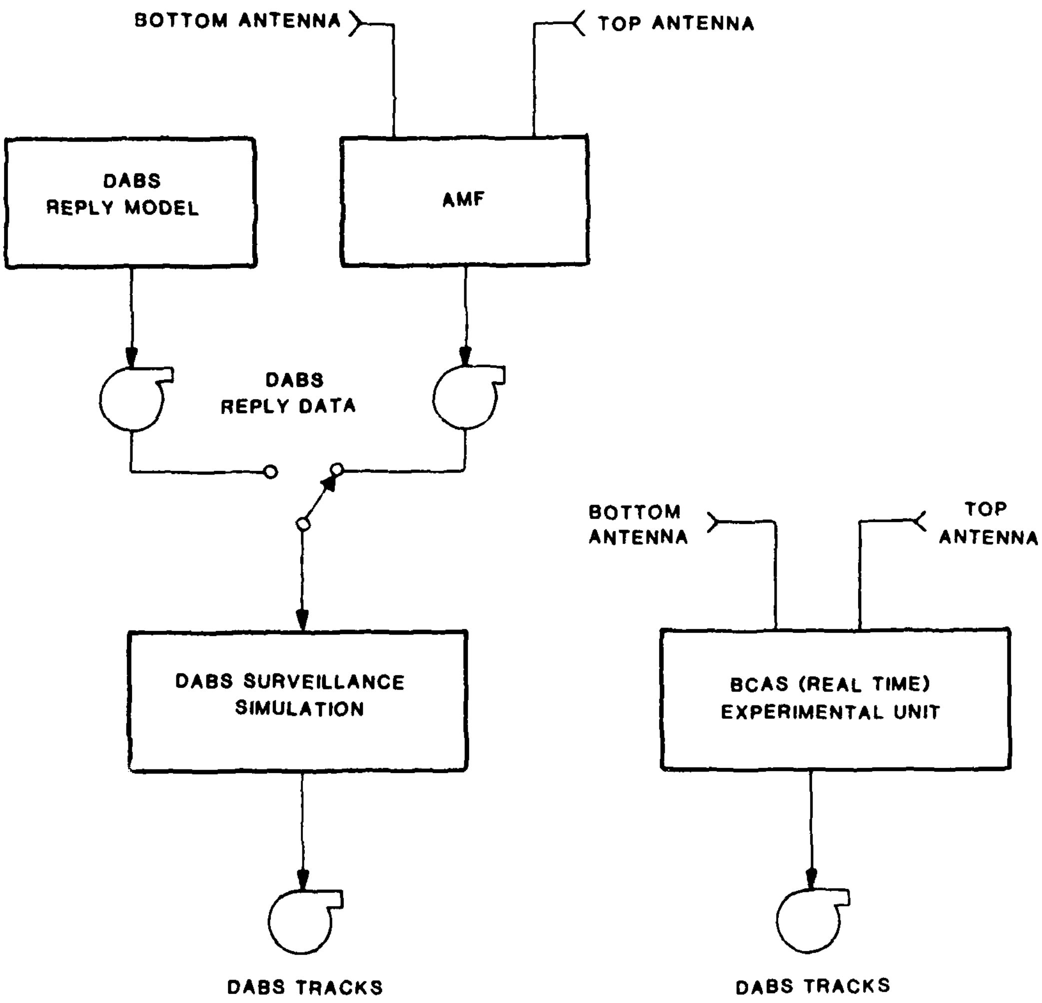


Fig. 2-1. DABS surveillance development facilities.

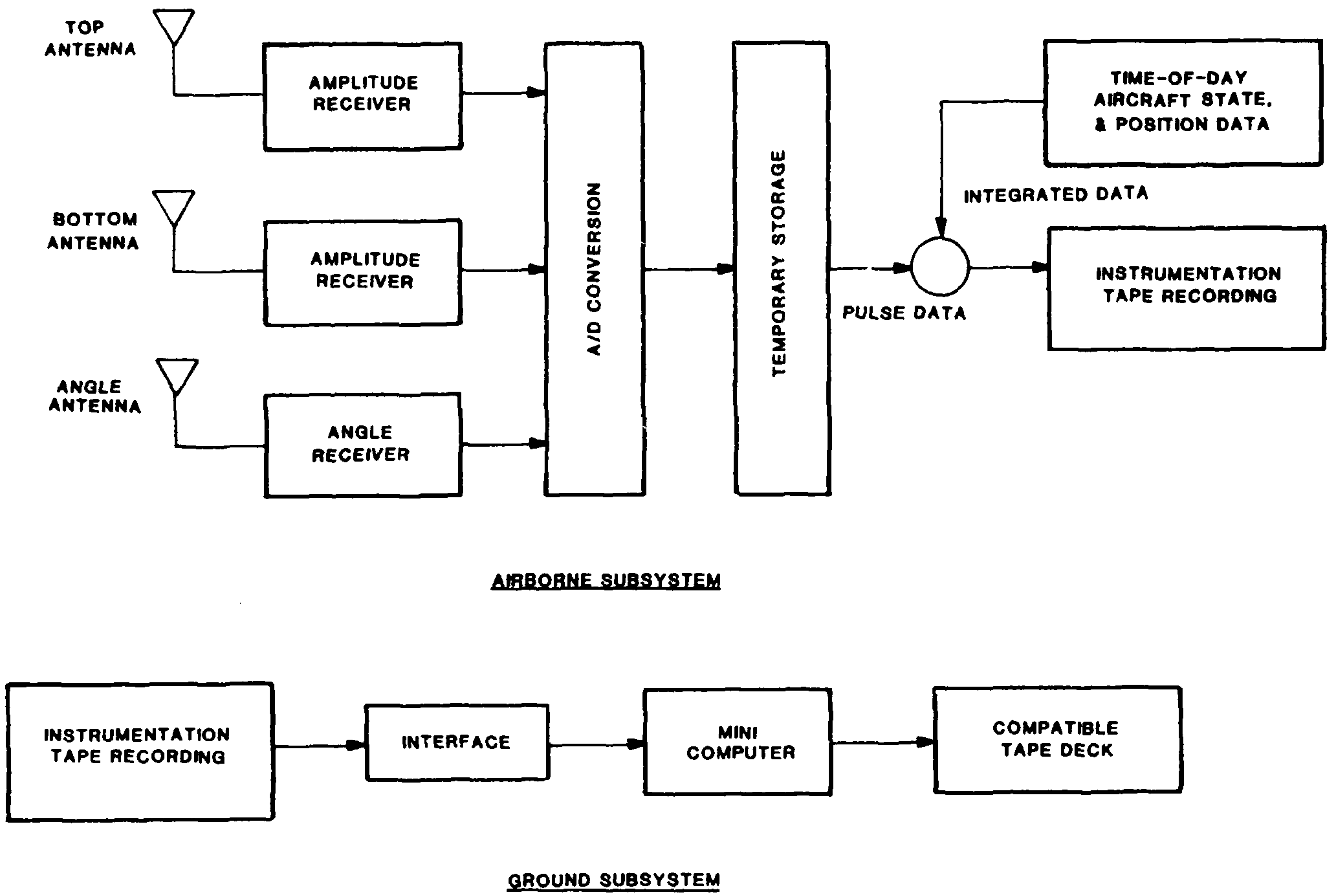


Fig. 2-2. AMF block diagram.

Fig. 2-3. AMF as installed in Piper Navajo.

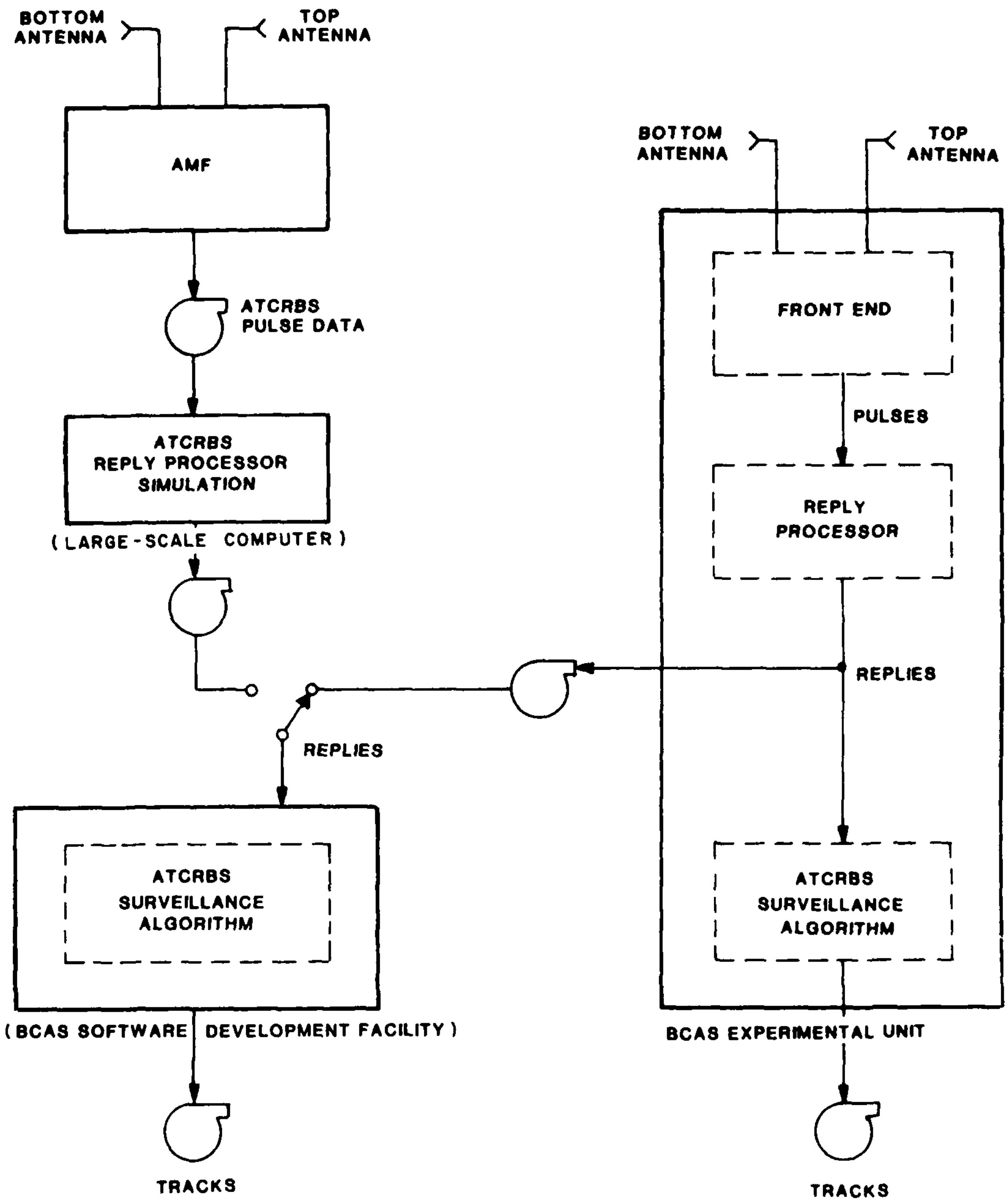


Fig. 2-4. ATCRBS surveillance development facilities.

The BEU, shown in Fig. 2-5, consists of an RF front end, digital signal processor, and a 32K word, 1 microsecond, minicomputer. The DABS transponder is physically independent of the BEU and uses a separate pair of antennas. A single 1090-MHz receiver is used by the BEU for the detection of transponder replies. DABS-mode interrogations are transmitted from the antenna which successfully communicated with the target on the last scan, and the same antenna is used for receiving the reply. ATCRBS-mode interrogations are alternated between the two antennas according to a fixed sequence, and in this case also, the antenna used for transmitting the interrogation is used for receiving the replies. The modulation control unit formats both ATCRBS and DABS interrogations. The ATCRBS/DABS reply detector includes video pulse processing and reply decoding circuits for both types of replies. False DABS preambles are rejected by the DABS reply decoder which decodes the DABS PPM format and the DABS parity code. The ATCRBS reply decoder searches the received pulse train for framing pulse pairs and decides which altitude code pulses are present in each reply. It also determines the target range, flags those code pulses which are potentially garbled, and rejects all phantoms (bracket pairs which could be code pulses belonging to other replies). All further reply processing and tracking is performed in software.

A photo of the BEU, Fig. 2-6, shows (from left to right) the computer, the processor, the modified instantaneous vertical speed indicator (for display of maneuver advisories), and the RF assembly.

During most of the flight tests in the Boston area, test aircraft were tracked from the ground by the Lincoln Laboratory DABS Experimental Facility using both DABS and ATCRBS transponder links. This provided increased safety during near-miss experiments and also provided surveillance data on all beacon equipped targets-of-opportunity.

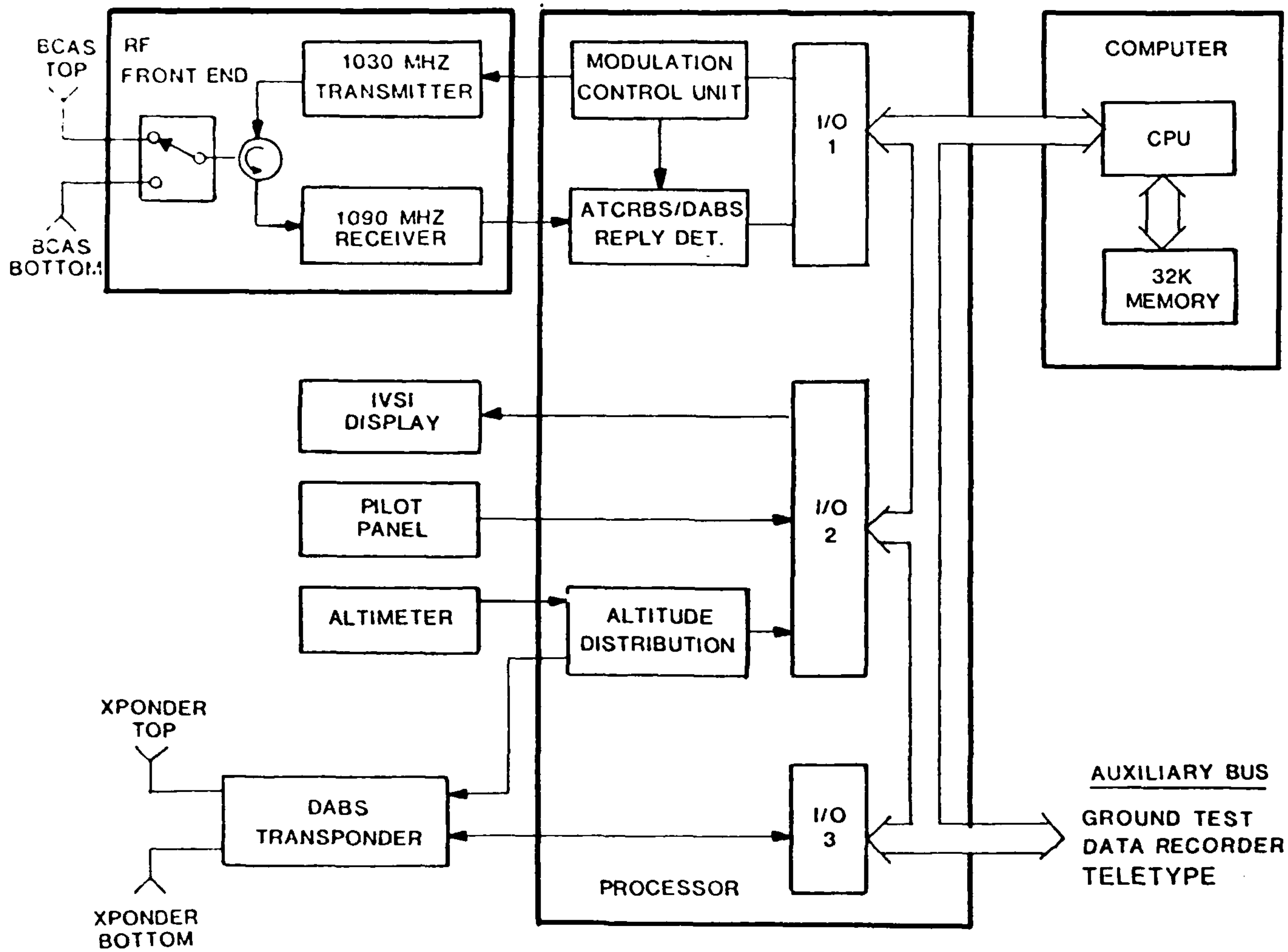
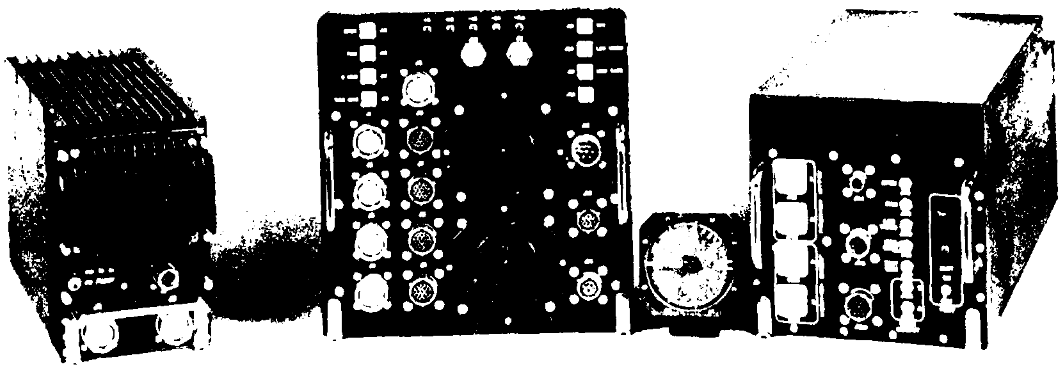


Fig. 2-5. BCAS Experimental Unit block diagram.



[illegible] Experimental Units.

3. DEVELOPMENT SUMMARY

3.1 Basic Link Mechanisms

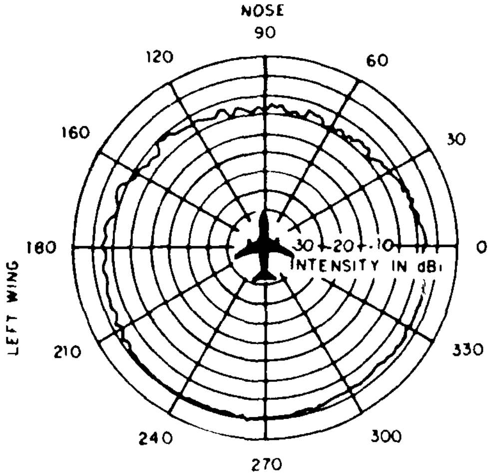
Air-to-air radio communications are subject to three basic disturbances that must be considered at the outset: power deviations, interference, and multipath. Power deviations include such adverse conditions as dips in the antenna pattern at either the transmitting aircraft or the receiving aircraft that can in some cases cause the received signal power to fall below the minimum detectable level. Interference occurs when the desired BCAS signal is received simultaneously with a signal transmitted from a different source (such as ATCRBS) in the same frequency band. BCAS uses two frequency bands: 1030 MHz for interrogations and 1090 MHz for replies. BCAS is subject to interference in both bands. Multipath occurs when a signal is reflected off the earth's surface giving rise to an echo which overlaps the desired signal.

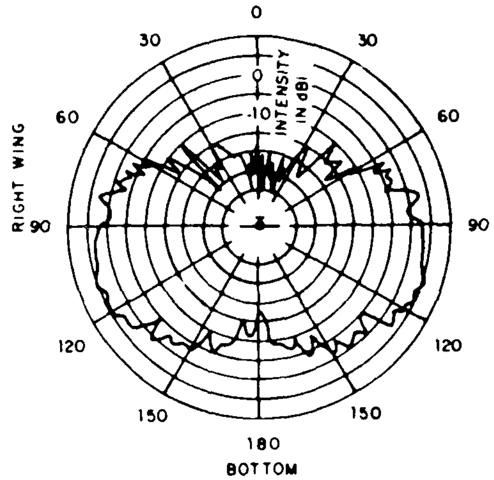
3.1.1 BCAS Link Power Budget

The air-to-air power budget is the relationship among transmitter powers, antenna gains, receiver sensitivities, etc. that determines whether or not receiver power levels are adequate. In the design of BCAS there is some freedom of choice of specifications for the BCAS interrogator power and receiver MTL (Minimum Triggering Level). Interrogator power should be high enough to provide adequate link reliability while being low enough to prevent interference problems. The question of providing adequate link reliability for BCAS was addressed in a study of RF power deviations. The study makes use of aircraft antenna gain data resulting from a model measurement program (an example of which is shown in Fig. 3-1), and is otherwise analytical. It is concluded that appropriate nominal design values are transmitter power = 500 watts and receiver MTL = -77 dBm (referred to the BCAS unit). It was shown that these values provide sufficient power margin at the air-to-air ranges appropriate for BCAS (which extend to 11 nmi to allow for the possibility of closing rates as high as 1200 knots) to allow for adverse power deviations that might result from aircraft antenna gains, antenna cabling, and the expected transmitter and receiver deviations due to manufacturing nonuniformities and aging. The results of this study are documented in more detail along with a discussion of the conditions of the study in Ref. 3.

3.1.2 Interference

BCAS interrogations are transmitted at 1030 MHz, where the primary sources of interference are ATCRBS interrogations and suppressions transmissions. 1030-MHz interference has been extensively studied in the DABS program. While the 1030-MHz band contains interfering signals occurring at significant rates, nevertheless it has been established that under almost all conditions the transponder reply probability remains high, typically 90% or more in either the DABS or ATCRBS mode. Perhaps the most useful characterization of 1030 MHz signal environment is the data resulting from airborne measurements recorded by the AMF. Ref. 4 summarizes data recorded during flights along the East Coast, giving interrogation rates, suppression rates and their power distributions, plus a detailed breakdown into the





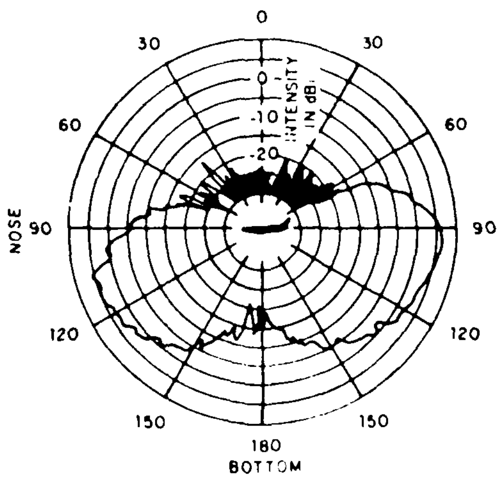


Fig. 3-1. Aircraft antenna patterns, from model measurements (Grumman Gulfstream; bottom mounted, rear antenna, flaps up, wheels up).

portions contributed by separate interrogators. Similar data recorded in the LA Basin is documented in Ref. 5.

Transponder replies, transmitted at 1090 MHz, are subject to the interfering effects of ATCRBS and DABS fruit. The term "fruit" refers to asynchronous transponder replies reaching a receiver -- asynchronous in the sense that they are not replies to interrogations transmitted from this equipment. Fruit rates received by an airborne system with omnidirectional antenna can be quite high, particularly when flying in areas of high traffic density and/or high rates of interrogation. Because of these high rates, the effects of fruit on BCAS may be significant in some cases. In addition to analytical studies of fruit and its effects on BCAS, a measurement program was undertaken. Fruit rate was measured using the AMF, in flights along the East Coast from Boston to Washi gton and in the LA Basin. The results of these measurements are summarized in Fig. 3-2 and are documented in more detail in Ref. 4. The report gives fruit rate as a function of altitude, geographical location, and receiver threshold, for receptions on both top-mounted and bottom-mounted aircraft antennas. The highest observed fruit rates, approximately 10,000 replies per second, occurred in the LA Basin.

To complement the measurements, a first-order fruit prediction model has been defined. The brief statements in Fig. 3-3 constitute the full definition of this model. In Ref. 6, predictions of this model are compared with the measurements, generally showing favorable agreement in absolute fruit rate, in power distribution, and in the functional dependence on traffic density.

3.1.3. Multipath

Ground bounce multipath has been measured during a variety of experiments documented in Ref. 7. Figures 3-4 and 3-5 illustrate typical replies with specular and diffuse multipath as observed at the log video output of a BCAS receiver. Figure 3-6 is an example of data from ref. 7 that indicates the effects of antenna diversity on the multipath power levels. Both aircraft were at 9500 ft. altitude and flying level over ocean. The flight paths diverged slightly, so that as time passed, results could be obtained as a function of range. Values of range are marked along the top of the figure. The use of a top-mounted antenna is seen to greatly reduce the effects of multipath in transmissions to an aircraft that has only a bottom-mounted transponder antenna. In this respect, the data in Fig. 3-6 is typical of results obtained at other altitudes and at other graphical locations.

Techniques which further reduce the effect of multipath on link performance are described in following sections.

3.2 DABS Surveillance

The design and validation of the DABS surveillance algorithm (Ref. 8) involved a large number of computer simulations using link models and data acquired using the AMF. This section highlights the principal experiments which validated the various surveillance techniques incorporated in the final BCAS design.

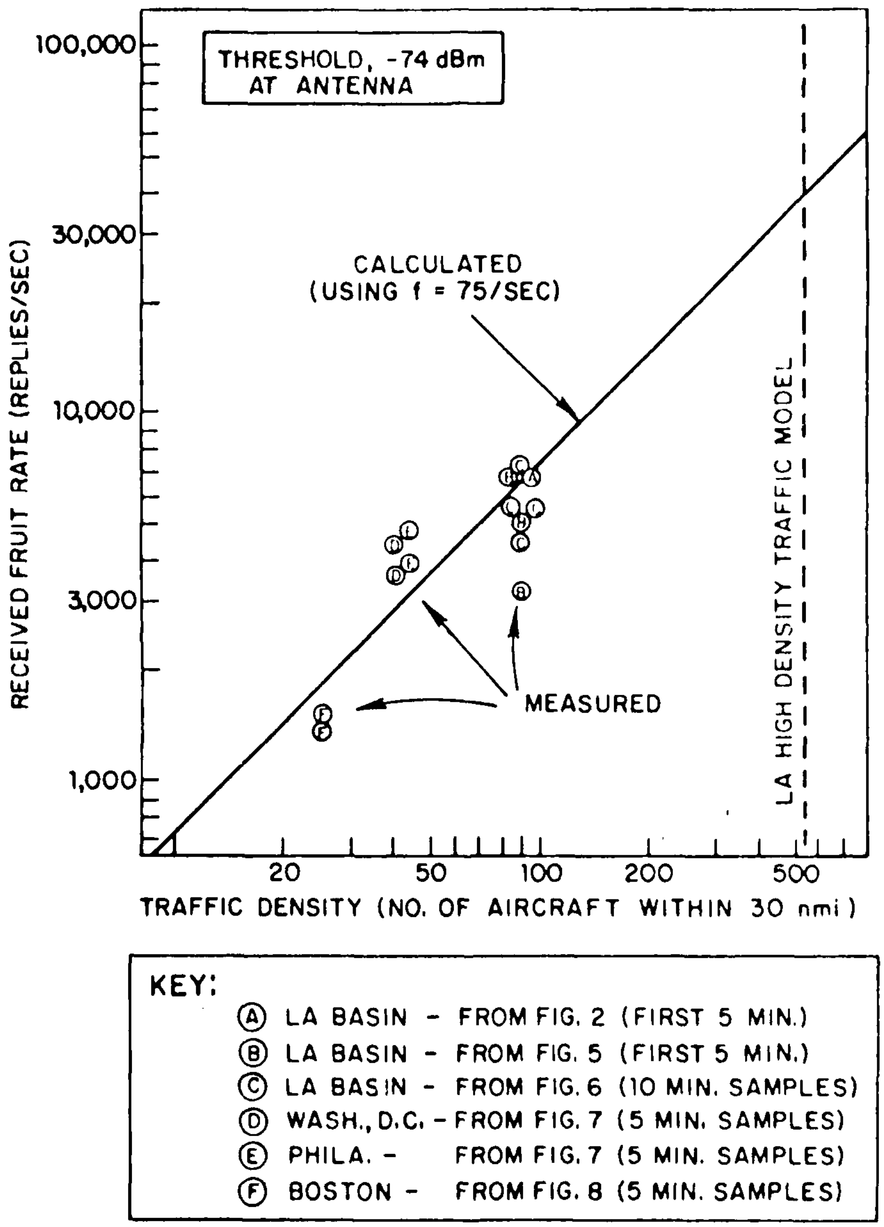


Fig. 3-2. Airborne measurements of ATCRBS fruit.

IDEALIZATIONS:

1) REPLY RATE = f replies/sec, A CONSTANT FOR ALL AIRCRAFT (TYPICALLY f = 150/sec)

2) TRANSMITTER POWER = 500 w LESS 3 dB CABLING LOSS FOR ALL AIRCRAFT

3) AIRCRAFT ANTENNA GAIN = 0 dB IN ALL CASES

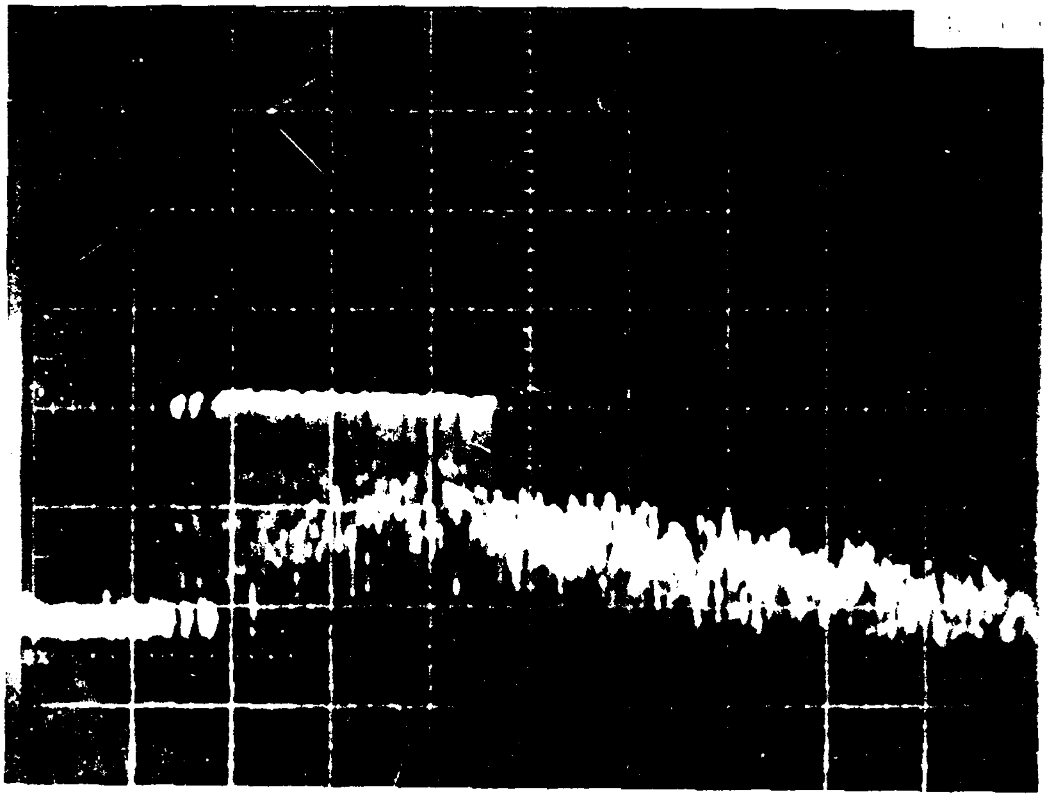
RESULTING FORMULA:

$F = f \times N$ (30 nmi)

N(R) = NO. OF AIRCRAFT WITHIN RANGE R

THIS GIVES THE TIME AVERAGE RECEIVED FRUIT RATE COUNTING ALL REPLIES OVER -74 dBm REFERRED TO THE ANTENNA. TO APPLY TO ANY OTHER THRESHOLD, CHANGE THE RANGE FROM 30 nmi BY 2:1 FOR EACH 6 dB CHANGE.

Fig. 3-3. Mathematical model for predicting airborne fruit rate.



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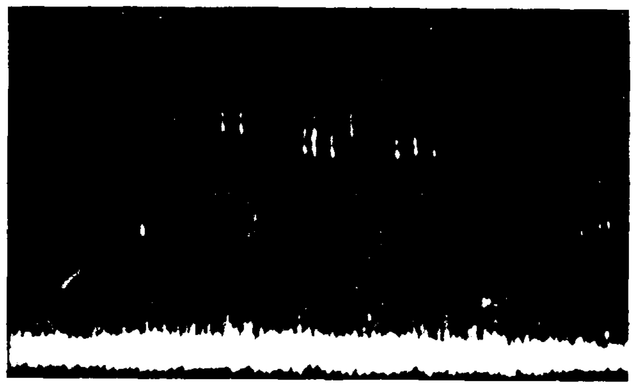
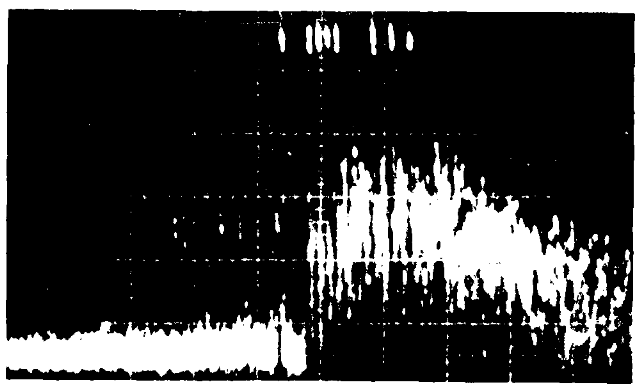
RECEIVED POWER, LOG VIDEO (8 dB / div.)

TOP ANTENNA



BOTTOM ANTENNA



TIME (10 μs / div.)

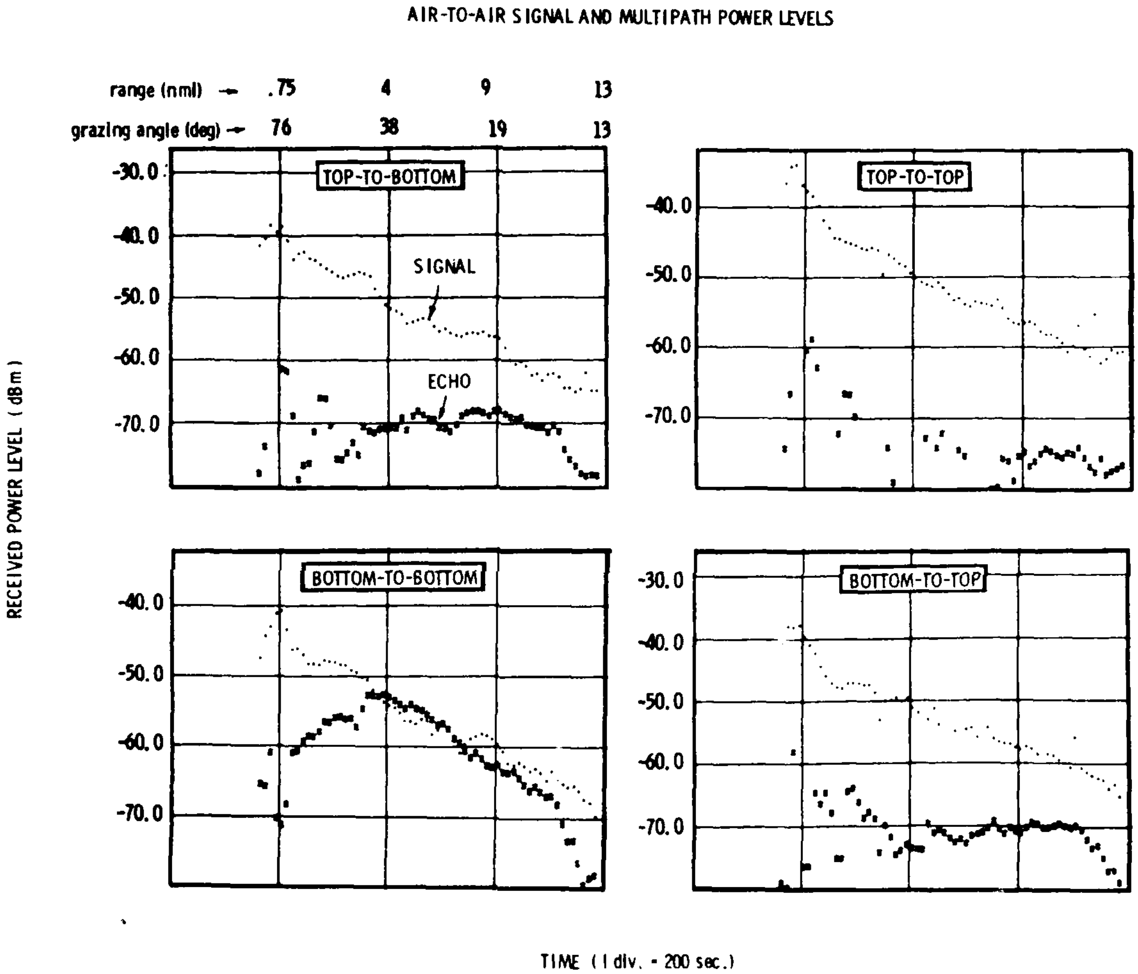


Fig. 3-6. Air-to-air signal and multipath power levels.

3.2.1. Multipath and Fruit

The following results are based on data acquired during air-to-air encounters flown over an urban Los Angeles area in 1978.

In general, the flight data gathered by the AMF indicated that significant multipath garbling occurred on both interrogation and reply links associated with bottom mounted antennas. Several distinct mechanisms which generated false reply preambles were directly attributable to surface scatter effects. Also, multipath interference received on the BCAS bottom antenna was a major factor in preventing the error correction system from improving BCAS link performance more than it did.

Fruit rates measured during the Los Angeles flights were 2 to 5 times higher than in the Boston area, but low enough to not significantly degrade performance via reply garbling. However, in conjunction with multipath signals, the fruit environment gave rise to the receipt of a considerable number of false reply preambles on the BCAS bottom antenna.

3.2.1.1 Overall Link Performance

Fig. 3-7 shows link round reliabilities for two head-on encounters over the Los Angeles area. Performance is shown here as a function of range, with range values marked as negative during the converging portion of each encounter. Fig. 3-7a shows data from an encounter in which the remitter aircraft was equipped with dual antennas and a DABS diversity transponder. Fig. 3-7b is from an encounter in which only a bottom-mounted antenna was used on the remitter aircraft.

The link round reliability curves in Fig. 3-7a indicate that during convergence the link reliability on the BCAS top antenna link exceeded 50% out to a range of 21 nmi, while the BCAS bottom antenna link reliability exceeded 50% out to a range of 23 nmi. Within 10 nmi, performance via the top BCAS antenna is about 90%. Link failures are believed to be due to the combined effects of interference and multipath. (It should be noted that a per-interrogation reliability of 90% results in very high tracking reliability). The remitter diversity system selected the top antenna about 95% of the time. The BCAS bottom antenna reliability dropped below 50% during divergence for range from 5 nmi to 11 nmi primarily because the interrogation signal strengths at the remitter were such that the bottom antenna was selected a significant number of times, thus introducing multipath interference. However, since round reliability did not drop below about 40% at any range within 15 nmi, and since in the past, the surveillance processor has successfully tracked aircraft when link reliabilities were considerably less than this, the link reliabilities shown in Fig. 3-7a are deemed to be adequate on both BCAS top and bottom antenna links to support surveillance processing.

A typical head-on encounter in the LA area with the remitter using only a bottom antenna is shown in Fig 3-7b. An improvement in air-to-air link performance associated with transponder diversity is clearly evident in Fig. 3-7. Yet the link performance in the non-diversity case is quite good in an absolute sense, and appears to be adequate for BCAS purposes.

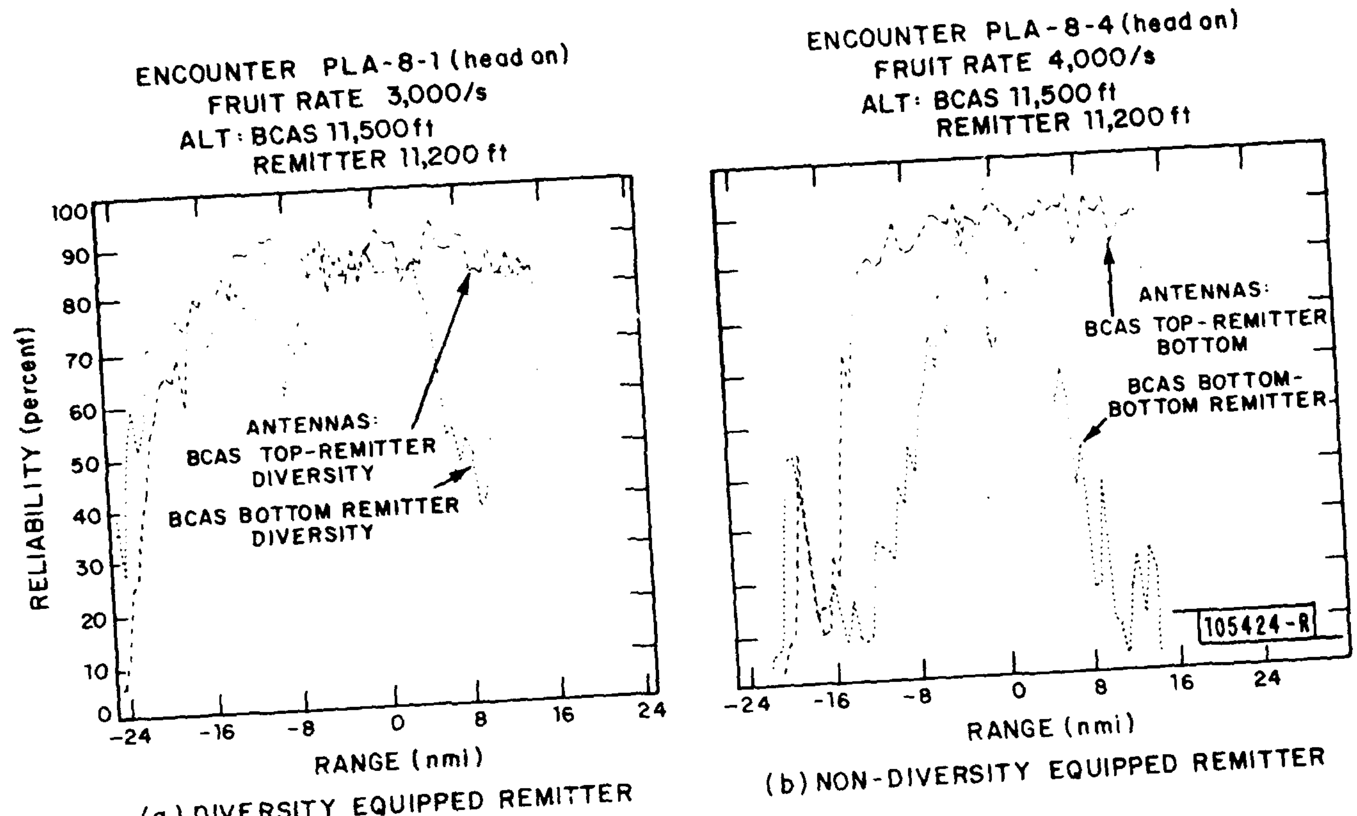


Fig. 3-7. Link round reliability for head-on encounters over Los Angeles.

In both encounters, consideration of link round reliability computed in the absence of error correction indicates that error correction provides no sigificant improvement in link reliability. Occasionally a 10% increase in link reliability occurred, but improvement was generally less than 5%.

Reply signal strength data indicate that received reply power exceeded the BCAS receiver detection threshold for all four antenna combinations for ranges out to 25 nmi. The remitter used in the experiment had a reply transmit power of 380 watts (at the transponder output port) rather than the nominal of 500 watts.

3.2.1.2 Effects of Multipath Interference

There were three main aspects of multipath interference: (1) BCAS transmissions on both interrogation and reply links were garbled, directly reducing link reliability; (2) many reply bits were declared with low confidence, thus preventing the error correction process from being initiated in many cases, and (3) a considerable number of false reply preambles were detected on the bottom BCAS antenna.

Evidence of direct multipath interference may be deduced from the head-on encounter data in Fig. 3-7 by making two comparisons. In both the diversity and the non-diversity cases, the top BCAS antenna exhibited higher link reliability over a wider span of ranges than the bottom BCAS antenna. A comparison of Fig. 3-7a with 3-7b indicates that a BCAS link with a diversity remitter antenna is effective over a much larger range span than a link which employs only a bottom remitter antenna.

In Fig. 3-7b, a 15% dip in link round reliability was observed near crossover on the bottom-to-bottom antenna link. The interrogation link reliability did not exhibit any pronounced dip in the crossover area. Thus the dip in round reliability must have been due to a reply link interference phenomenon. The probability of reply preamble reception over the bottom-to-bottom link also exhibited a drop near crossover. The signal strength data did not indicate any significant drop in received power near crossover. The aircraft altitudes and ranges were such that the minimum multipath delay was ~22 μs, while the direct propagation time was ~1.6 μs. Thus since the forward scatter multipath could not overlap the preambles, no preamble garbling due to multipath could have occurred.

The most probable explanation for the 15% dip in link reliability is as follows. When a DABS BCAS interrogation is transmitted, a considerable amount of 1030 MHz energy is backscattered by the surface of the earth and received at the BCAS aircraft. The transponder on the BCAS aircraft can easily be triggered by this backscattered DABS interrogation, and cause a suppression of the BCAS receiver (via the aircraft mutual suppresssion bus) at the time of

the transponder reply. The backscatter signal can last for many microseconds, the actual duration depending on the scattering surface. It is thus possible for the transponder to have triggered after a long enough delay following the DABS interrogation to have caused the BCAS receiver to be suppressed during the receipt of the DABS reply preamble. Subsequent incorporation of an extended aircraft suppression signal to the transponder eliminated this phenomena.

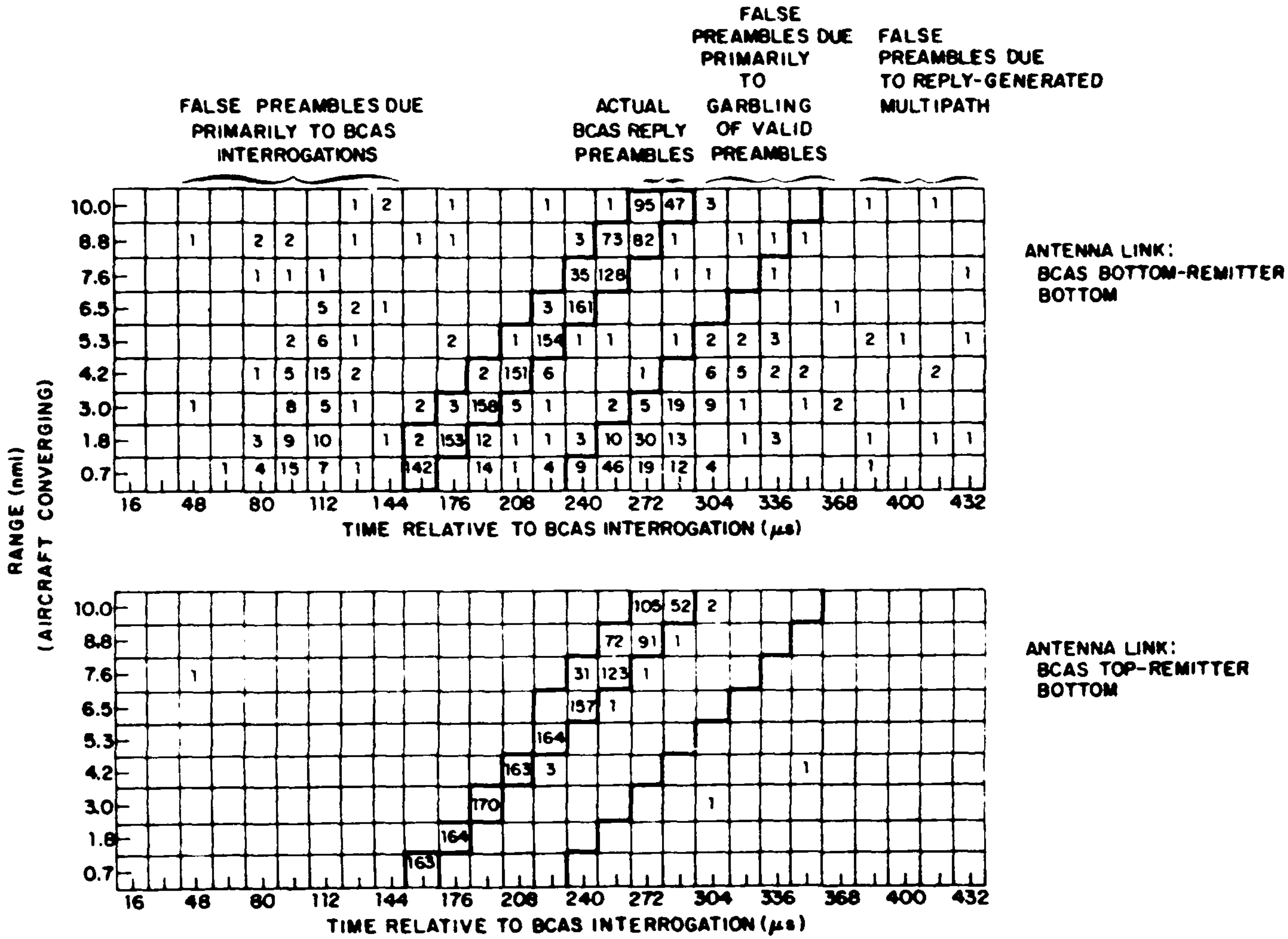
In addition to the suppression of the BCAS receiver when the BCAS aircraft transponder replies to a backscattered DABS interrogation, the DABS reply preamble detector in the BCAS unit may become inhibited as a result of false preambles. While there are several mechanisms which generate false reply preambles, one mechanism due to the backscattered interrogation is the overlap of the transponder reply and backscattered reply signals in such a way as to synthesize a signal meeting the preamble detection criteria. When this happens, the preamble detector is inhibited at the time that the BCAS reply should be received. This phenomena also has been eliminated by the use of the extended (~200 μsec) suppression signal.

DABS interrogations are not the only causes of false reply preambles. There appear to be three other distinct mechanisms of false preamble generation: (1) detection of a reply preamble pattern in the DABS reply message block when the real preamble is garbled and therefore not detected, (2) preamble synthesis by the multipath following a DABS reply, and (3) preamble synthesis as a result of the interaction between fruit and its multipath. The last mechanism is independent of BCAS transmissions.

Measurement results are presented in Fig. 3-8 in a way intended to show the timing characteristics of these false preambles. The figure gives the number of DABS preambles received in six second intervals vs. range and vs. time from the BCAS interrogation. Numbers of false preambles due to the first three mechanisms are indicated.

In addition to head-on encounters, the air-to-air link characterization measurement included a number of angular encounters. These involved crossing angles of 150°, 120°, 90°, 60° and 0° (a tail chase geometry), and were all done with the target being diversity equipped. Results were the same in all major respects as what was seen in the head-on encounters. Round reliabilities on the BCAS top antenna were consistently in excess of 50% within 15 nmi. Link reliabilities on the BCAS bottom antenna were also high except in the presence of significant multipath interference.

The only feature of the angular encounter results which was different from the head-on encounter results was the pattern of remitter diversity antenna switching. Variations in antenna gain resulted in different interrogation signal strengths at the remitter top and bottom antennas causing corresponding antenna selections.



NOTE: THE NUMBERS IN EACH BLOCK CORRESPOND TO SIX-SECOND ACCUMULATIONS. THERE ARE 180 INTERROGATIONS IN EACH SIX-SECOND INTERVAL.

Fig. 3-8. DABS reply preamble counts.

The significance of the DABS-mode flight data is as follows:

Interference Phenomena

- Fruit environments such as experienced in the Boston and Los Angeles areas have little impace on BCAS link performance.

- Multipath interference can severely degrade BCAS bottom-to-bottom antenna link performance.

- Error correction is ineffective in the presence of multipath interference.

- Combinations of fruit and multipath interference can result in false reply preambles. In some cases such false preambles can degrade discrete link performance at close range while in other cases they can increase BCAS receiver dead-time and decrease squitter acquisition reliability. Seen on a BCAS top antenna, these effects are minimal.

System-Level Observations

- The performance of the BCAS top antenna link appears to be adequate to support BCAS surveillance in the Los Angeles fruit environment.

- In addition to minimizing direct multipath interference on the BCAS link, the use of the top mounted BCAS antenna virtually eliminates the reception of false reply preambles. The use of an extended suppression signal significantly reduces the number of bottom antenna false preamble detections.

- Error correction does not significantly improve link performance, and it is not necessary for adequate link reliability in present day fruit environments.

3.2.1.3 High Speed Non-Real-Time Simulation Results

Link data from the flights flown in Los Angeles in 1978 was also used as a data base for the non-real-time DABS surveillance processor (Fig. 2-1) . In addition to processing of the data exactly as recorded, the data were also processed with a simulated 2:1 speedup factor. This was done in order to exercise the surveillance algorithms with encounters at higher speeds than the maximum achievable with the experimental aircraft.

Fig. 3-9 presents the performance for five of these encounters. In all cases the system was able to establish track well before entering the threat volume. This was also true (as shown) when the encounters were speeded up by a factor of 2 and played through the processor. The range at which DABS-mode tracking begins is controlled to a large degree by the maximum speed parameters of the two aircraft. These maximum speeds were both set at 300 knots in the processing at real speed and were set at 600 knots in the processing at twice real speed. As a result, the tracks in the speeded-up cases generally begin at longer ranges.

Details from the computer summary for the head-on encounter are given in Fig. 3-10. It can be seen that the squitters were received quite regularly. The target had been placed in dormancy prior to the beginning of the time interval shown here. A squitter was received shortly after the release from dormancy at a range of 13 nmi. The target was again placed in dormancy, this time for 36 seconds. Fig. 3-10 shows the target coming out of this second dormancy at scan 130 and again being acquired and placed in dormancy for 14 seconds. Upon emerging from this dormancy, this squitter is received, acquisition is successful again the target is considered a sufficient threat so that it is placed in roll-call at scan 151.

Tracking proceeds successfully with the bottom antenna for the next 26 scans. The target is returned to acquisition processing every 6 scans for validation purposes for a total of 4 times. This is done to ensure that a multipath return has not somehow been introduced into the track file. After scan 175 the target is considered permanently validated (no more "A's" in the STATES row).

At scan 177 the system was unable to obtain a valid reply after 2 interrogations for the bottom antenna and therefore switched to the top antenna. Tracking proceeded with no problem until scan 187 when it switched back to the bottom until scan 201 when the top antenna was selected again. The simulation was terminated at 220 seconds.

The surveillance algorithm functioned satisfactorily since at no time during roll-call were more than 3 interrogations required to obtain a valid reply. A detailed description of the DABS surveillance processing algorithms is given in Ref. 8.

3.2.2. Reply Preamble Detector

The preamble of a DABS reply consists of four 0.5-μsec pulses (Ref. 9, page 19). It is the function of the preamble detector to trigger on the presence of this signal and obtain from it a time-of-arrival synchronization. This should be accomplished not only when the reply arrives in the clear, but also when it arrives in the presence of considerable amounts of interference and multipath. The detection criteria in the original design is that valid pulses are detected in all four positions of the preamble waveform and, in addition, at least two of the pulses are detected with clear leading edges. A valid pulse is defined as one in which at least 75 percent of the quantized-video samples are 1's. A clear leading edge is defined as a valid pulse for which the quantized video changes from 0 to 1 at the beginning of the pulse. An example of a circuit that implements these functions is shown in Ref. 9, page 81.

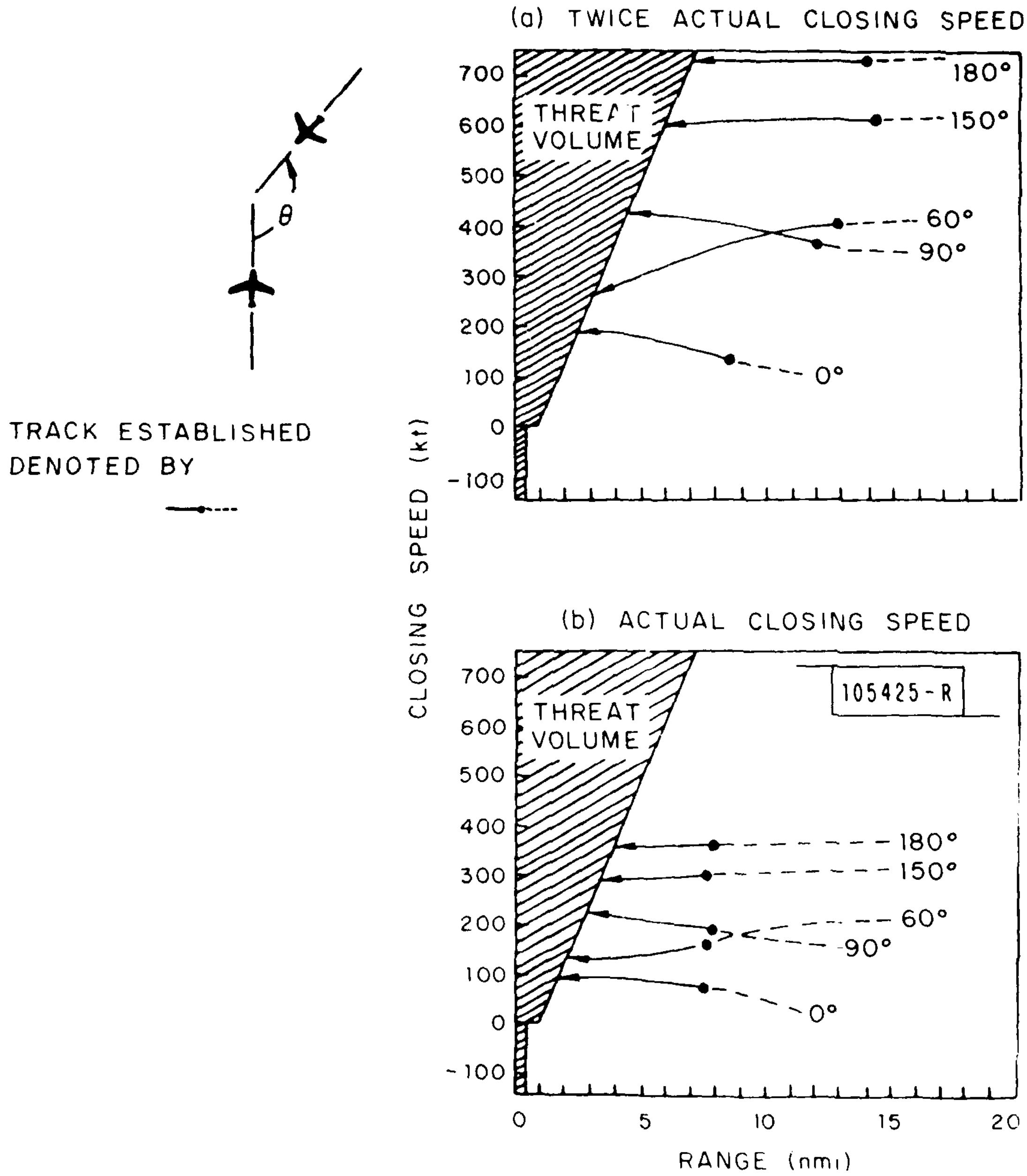


Fig. 3-9. Modified surveillance processor performance for five encounters.

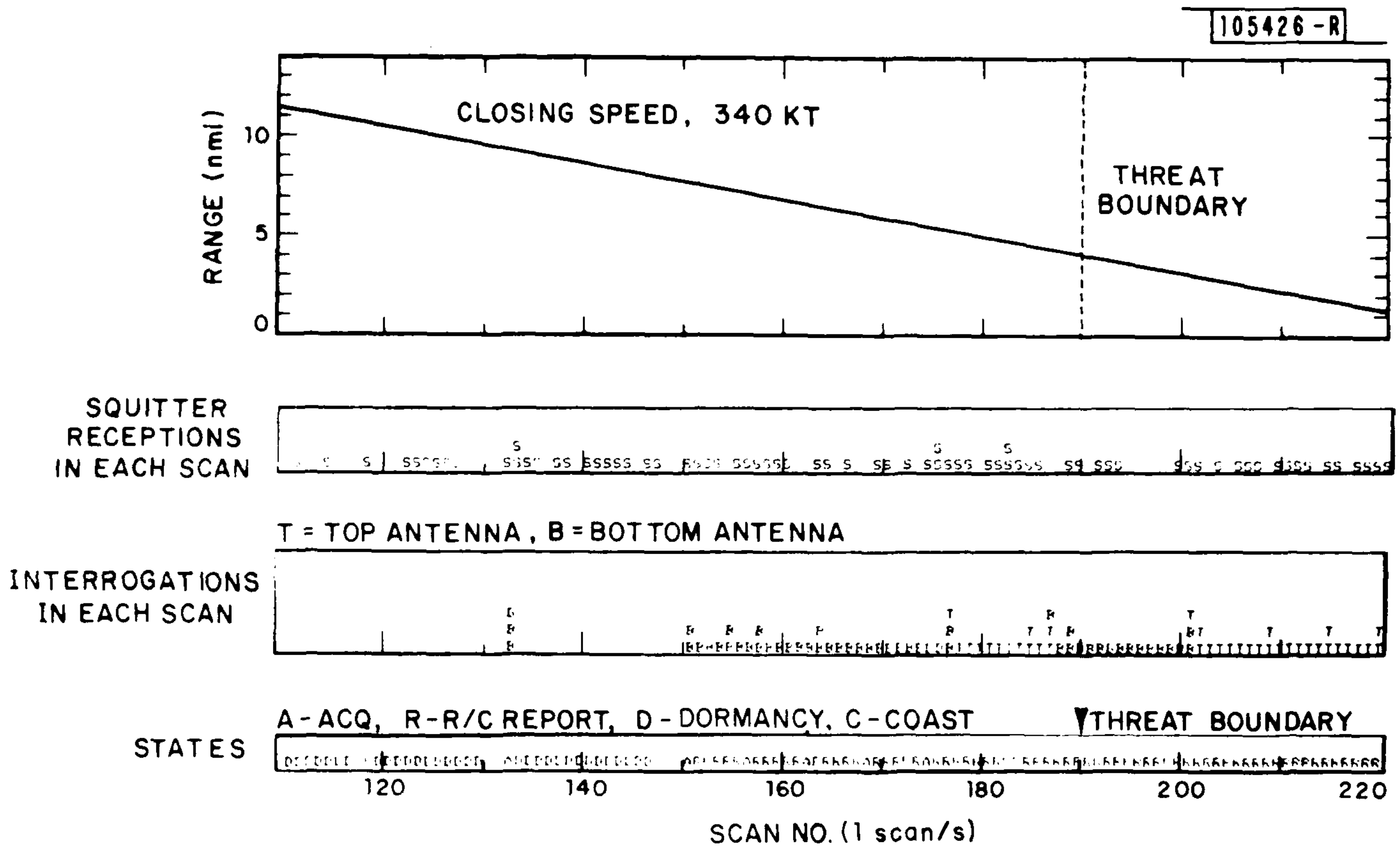


Fig. 3-10. DABS-mode BCAS performance (non-real time processing).

The problem with this design, is that multipath can interfere with the leading edge detections when defined in this way. The requirement for a zero of quantized video just prior to a pulse is unnecessarily strict. A scenario in which an unnecessary degradation will occur is the following:

- two aircraft at low altitude (about 2000 ft.) where the differential multipath delay is small (a few μs or less).
- short range between the aircraft (several miles) such that the power level of the direct signal is high.
- signal-to-multipath ratio of about 20 dB (which is typical for earth reflection) such that the multipath, while small relative to the signal. is nevertheless above receiver threshold.

With multipath power above threshold. the required zero of quantized video prior to a pulse is often destroyed. As a result, the requirement for at least two clear leading edges will often not be met in this scenario. It seemed unnecessary to insist on the zero of quantized video, which is an absolute power test rather than a relative power test. In this case. the signal pulses are 20 dB above multipath and so their leading edges could be reliably detected even when multipath does destroy the zero. In fact, the BCAS pulse processor already contains a leading edge detector circuit, used in the ATCRBS mode, that detects leading edges ot this sort (preceded by reception above threshold). There were two obvious ways to improve the design of the DABS preamble detector: (1) use the existing ATCRBS-mode leading edge detector. (2) use dynamic thresholding during the DABS preamble. We believed that either technique would be effective. In assessing this change thro n air-to-air experiments, technique (2) was selected because the hardware change could readily be accomplished by use of the existing dynamic threshold circuit whose present purpose is for confidence bit detection during demodulation of the DABS data block.

Flight data was analyzed further in an attempt to get a quantitative indication of the improvement to be expected by dynamic thresholding. Fig. 3-11 is a plot of the time-of-arrival of DABS preambles. as detected by the unmodified circuit, shown as a function of mission time. Each preamble detection is represented by one plotted symbol. Two types of symbols are plotted to distinguish between:

c --(data correct) a preamble detection followed by a correctly demodulated data block.

n --(data not correct) a preamble detection followed by a demodulated data block that is not correct.

The DABS error detection code is used as the means of distinguishing between the two cases. When a 56-bit data block satisfies the parity test, it is said to be correct. False preamble detections sometimes occur at a time when a DABS reply is in fact being received. When this happens, the parity test fails. In Fig. 3-11, one clearly sees the synchronous pattern of detections

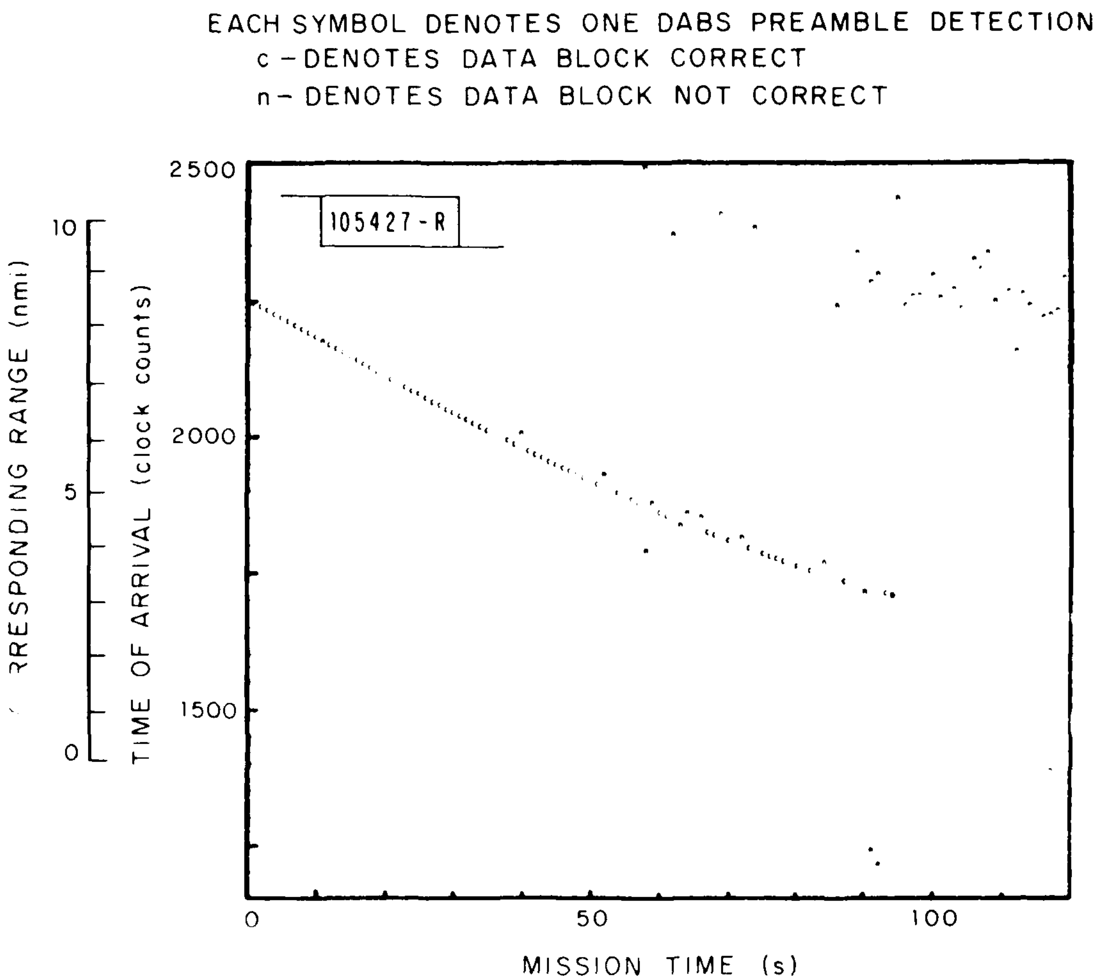


Fig. 3-11. DABS preamble detections.

that result from the real DABS replies. The set of synchronous detections were identified, and it was determined (by counting) what fraction of these are correct and what fraction are not correct. These two fractions are, respectively, estimates of the conditional probabilities:

P_c = P (data block correct/correct preamble detection)

P_n = P (data block not correct/correct preamble detection)

If the results showed that P_n is high, there would be little reason to expect any significant improvement in air-to-air performance after the preamble detector was improved. The results in Fig. 3-11 however show the opposite: that a large fraction of the synchronous detections resulted in a correct data block. This means that a more effective preamble detector would produce more reliable reply detection.

A preamble detector dynamic threshold circuit was incorporated in the AMF and later in the BEU's. This circuit raised the MTL to a value 6 dB below the P1 peak amplitude for the duration of the reply. Flight data was analyzed which verified that the expected improvement did occur and the design modification was accepted.

3.2.3. Squitter Detection

The BCAS DABS mode squitter design was tested by studying AMF airborne data recorded in the LA basin. One of the techniques used in the detection of squitters consists of counting confidence bits generated by the DABS reply processor. Low confidence bits are generated whenever the energy difference between the two PPM chip positions (determined by counting 8 MHz samples of the detected log video) is inconsistent with the data declaration. Should a reply contain too many low confidence bits, the reply is assumed to be false and is discarded. A study was conducted to determine the rate at which invalid DABS signals would be received, with and without the confidence test. These results. obtained as a function of the confidence-count threshold. provide information upon which to base an assignment of the value of the threshold.

When these measurements were made (March 1978). the AMF aircraft was engaged in encounters with a second aircraft equipped with a DABS transponder. The squitters transmitted by that transponder were in an old format, in which address and parity were separated, so that error detection could be applied upon reception. Since the data recording occurred prior to this error detection, it is possible to reprocess this data to simulate the new squitter design. The reprocessing procedure is simply to omit the error detection function.

Results of this processing are shown in Fig. 3-12, which gives the average rate at which invalid DABS listen-in signals were received. The rate,

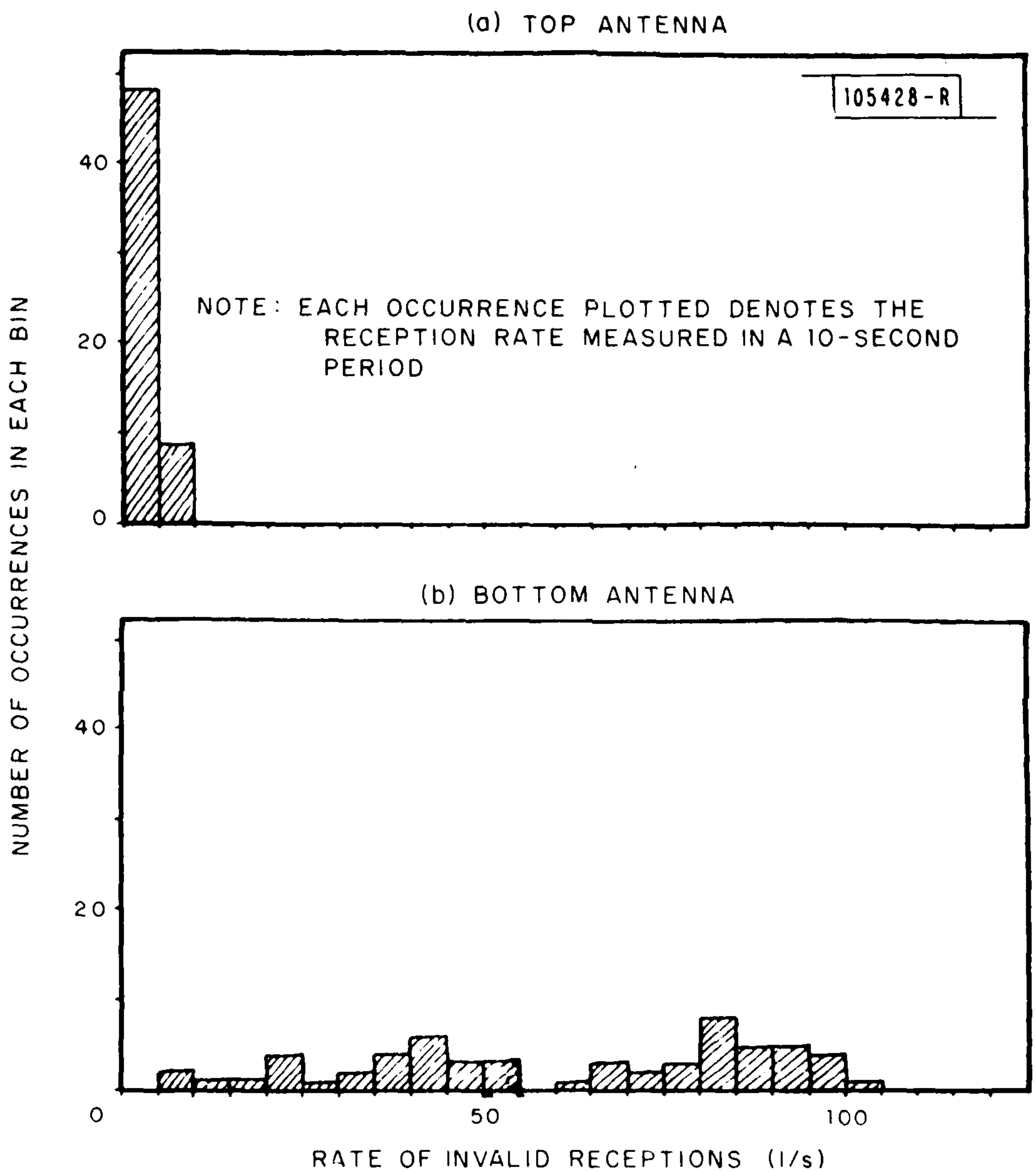


Fig. 3-12. Rates at which invalid signals are received in passive listening periods.

averaged over 10 seconds, was measured a number of times. the results of which are shown in histogram form in this figure. It is evident that invalid signals are numerous, occurring at rates as high as about 100 per second on the bottom-mounted antenna. When using the top-mounted antenna, the rates are much lower.

During the measurements, the receiving equipment alternated between passive-mode (listen-in) and active-mode periods. The passive mode occupied about 97% of the time, so that the rates plotted, in Fig. 3-12, are essentially the same as what would be measured if listening continually. Also, the receiving equipment alternated between top and bottom antennas, spending 50% of the time connected to each. Thus the active reception rates for each antenna are about twice the values shown in this figure.

The number of low-confidence bits in each reply is a variable. In order to see how often various values occur, the data was sorted into histograms, producing the results shown in Fig. 3-13. The distributions are presented in both differential form and cumulative form. Invalid receptions generally have more low-confidence bits than do valid receptions. Thus a test based on the number of low-confidence bits would provide effective discrimination.

It might also be expected that, among the valid receptions, those received on the top antenna would generally exhibit improved confidence bit counts relative to those received on the bottom antenna, these latter being more apt to be disturbed by multipath. The shape of the curve in Fig. 3-13(c) is consistent with this expectation. It suggests that essentially all of the top receptions (50%) have low confidence counts of zero, while the bottom receptions have counts ranging from 1 to 40, approximately uniformly distributed.

Based on these results, the threshold was established at 35. A reception with fewer than 35 low-confidence bits is accepted as a squitter candidate. Otherwise the reception is discarded. This test reduces the rate at which invalid receptions are accepted by 100:1 (from Fig. 3-13) to an absolute rate of about 1 per second (from Fig. 3-12). On the other hand. valid signals are accepted with about 93% probability (from Fig. 3-13).

This design achieves an effective separation of valid and invalid signals, while keeping the storage and processing requirements at a reasonable level.

3.2.4. Antenna Diversity

This section describes several experiments designed to determine whether there is a need for antenna diversity on either the BCAS or the remitter aircraft.

3.2.4.1 Link Performance and Received Signal Strength

Link data in the DABS mode was obtained during overland flights in the Boston area. The data presented here were obtained from 10 head-on encounters

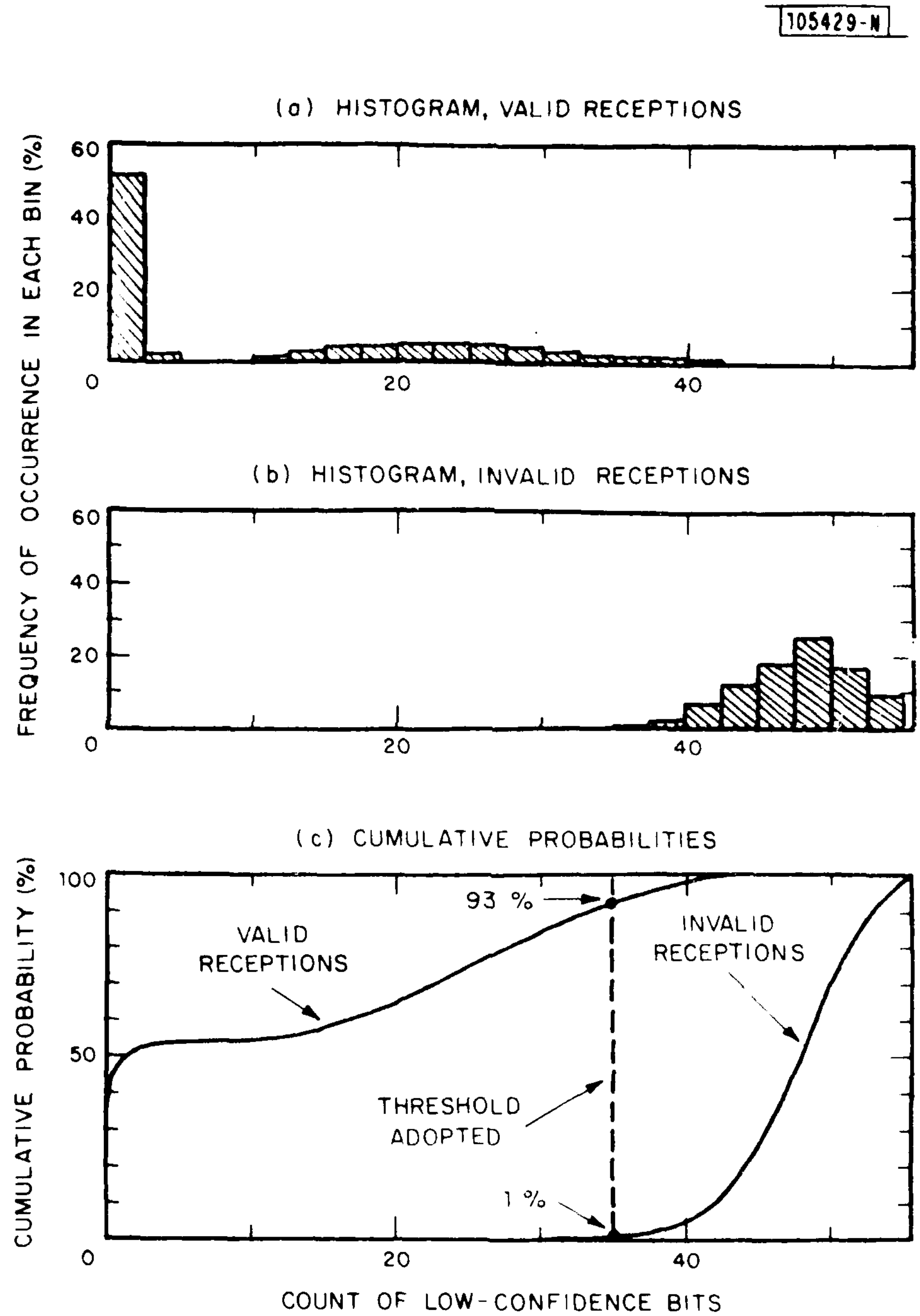


Fig. 3-13. Squitter measurement results.

between the AMF-equipped Cessna 421 and a Convair 580. A BCAS interrogator onboard the Cessna transmitted DABS interrogations alternately from top and bottom mounted antennas. The Convair was equipped with a DABS transponder connected to top and bottom mounted antennas. Five of the encounters were flown with the Convair operating in the diversity mode (Encounter Group A), and five in the non-diversity mode (Encounter Group B, bottom antenna only). In all cases the BCAS aircraft flew at a higher altitude than the transponder aircraft; see Table 3-2.

TABLE 3-2.

AMF (CESSNA) - CONVAIR 580 ENCOUNTER FLIGHTS OF 13 JUNE 1979

Encounter Group	Convair Antenna Group	Altitude (feet) AMF	Altitude (feet) Convair
A	Diversity	5500	2500
		5200	2500
		5000	3600
		5000	4500
		5000	4500
B	Bottom Only	5500	2500
		5500	2500
		5100	4000
		5000	4500
		5000	4500

Figures 3-14 and 3-15 present round reliability without error correction as a function of average received power at the AMF input. Each point on the plots represents 6 seconds of data (approximately 182 interrogations from a given antenna). The power levels plotted represent the arithmetic average of the received amplitudes in dB. Received power is quantized to the nearest dB. Transmit/receive antenna configurations for the four plots are as shown below:

Figure	Encounter Group	Transmission from AMF ----- Antenna	Remitter (Convair) Mode/Antenna
3-14(a)	A	Top	Diversity
3-14(b)	A	Bottom	Diversity
3-15(a)	B	Top	Bottom Antenna Only
3-15(b)	B	Bottom	Bottom Antenna Only

These plots illustrate the combined action of the AMF receiver and the remitter receiver along with the effect of interference. Without interference the plots would be expected to resemble the product of the two sensitivity functions with reliability increasing monotonically with signal strength.

The plot that most closely approaches this product is that given in Fig. 3-14(a) for the AMF top-to-remitter diversity. When the AMF bottom mounted antenna is used (Fig. 3-14(b)), many points with low reliability and high signal strength appear. If the remitter is limited to its bottom antenna, the results shown in Fig. 3-15 are obtained. When bottom antennas are used on both aircraft, high received signal strength by no means guarantees a good link.

Comparison of the four plots shows a consistent pattern in which degradation of the link is closely related to the amount of involvement of the bottom antennas. This is consistent with the results presented in 3.1.2 that show a large increase in multipath when interrogation takes place from the bottom antenna. The plots illustrate very clearly how multipath degrades the operating characteristics of the links for various antenna combinations. It may be concluded from these results that it is mandatory that the BCAS aircraft be equipped with a top-mounted antenna. The question of whether the BCAS aircraft needs also a bottom-mounted antenna is addressed in 3.3.5.2.

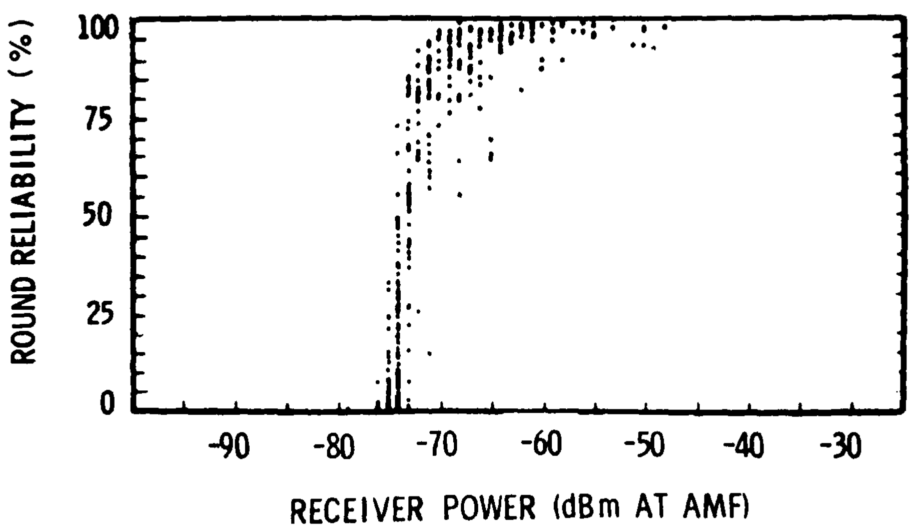
3.2.4.2 DABS Transponder Diversity Experiments

A set of data has been obtained which permits a specific comparison of the performance of BCAS surveillance of DABS transponders with and without diversity. Non-diversity transponders operate through a single bottom-mounted antenna. This section reports the results of this comparison and, as well, compares the performance with that of ATCRBS transponders which of course operate without diversity.

The plots that follow summarize performance in terms of "target reports" for the three modes. Target reports, the final output of the BCAS surveillance function, are passed to the threat-logic function of BCAS; at this interface any isolated replies or tracks of low confidence have been removed.

Specific examples are presented here of data obtained from 12 encounters flown with a Boeing 727 serving as the BCAS equipped aircraft (here equipped with the AMF). Data recorded was played back after the mission through processing which performed the BCAS surveillance functions. A Beech Bonanza served as the target aircraft. In all of these encounters. the BCAS aircraft was equipped with both top and bottom-mounted antennas.

(a) BCAS Top-Antenna to Remitter Diversity



(b) BCAS Bottom-Antenna to Remitter Diversity

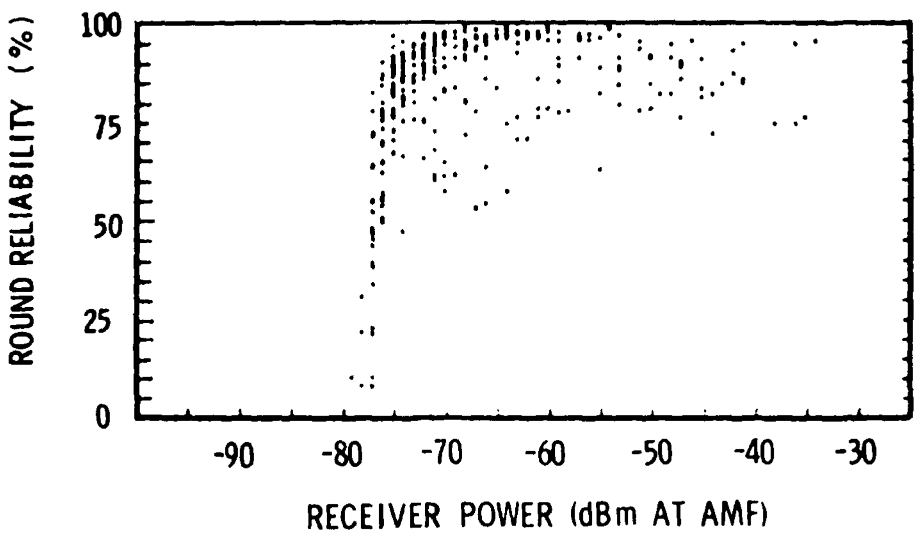
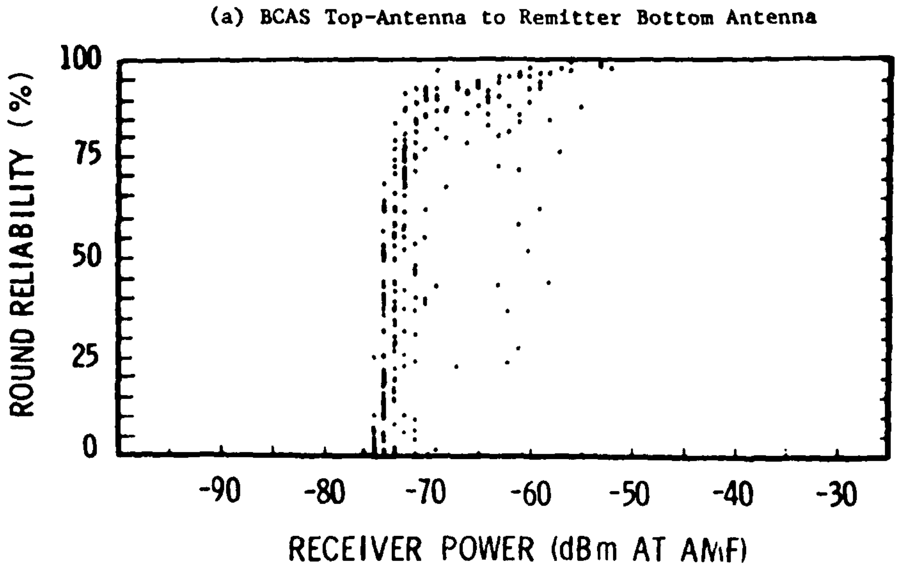


Fig. 3-14. Round reliability vs. received power level (diversity).



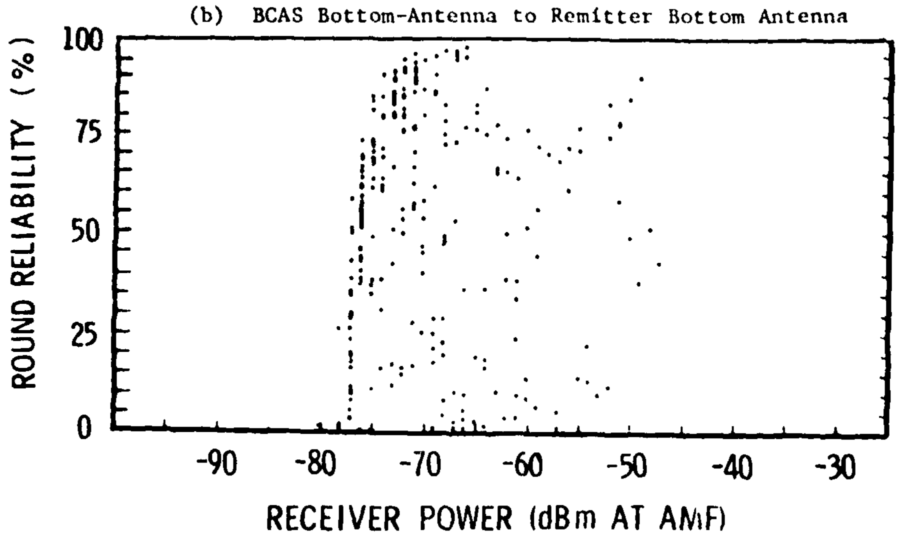


Fig. 3-15. Round reliability vs. received power level (non-diversity).

Three types of encounter geometries were flown: "head-on". "rapid descent", and "San Diego". Their flight paths are described in Fig. 3-16. These paths were selected in order to exercise BCAS surveillance under the most challenging conditions that are operationally significant. Factors that make these conditions challenging for BCAS are: low altitude (where multipath conditions are most severe). look-down angles which cause the bottom mounted antenna of the other aircraft to be shielded, and use of a large aircraft which causes more severe shielding of the BCAS top antenna in look-down geometries. These experimental encounters were selected with reference to the conditions under which mid-air collisions have occurred in the past. Fig. 3-17 compares these geometries and the geometries of a number of actual mid-air collisions previously studied by MITRE Corp. (Ref. 10, p. C-1 to C-3).

3.2.4.2.1. Results

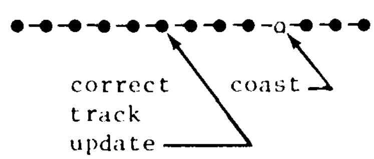
The results are shown in Figs. 3-18, 3-19 and 3-20 for all three encounter geometries over land. and in Fig. 3-21 for head-on encounters over the ocean. The symbols plotted denote the following:

E - establish the track (the first time data is issued as an output from the surveillance subsystem).

D - track drop

B - beginning of experiment

25 - location of the aircraft 25 seconds before point of closest approach (PCA)



In addition to the target report results shown in Figs. 3-18 through 3-21, the measured DABS interrogation rates are shown in Table 3-3 for the 6 DABS encounters conducted over land.

In the encounters involving a DABS diversity transponder tracking performance was perfect in all three encounters over land, and in head-on encounters over the ocean. This performance covers not only the important period within 25 seconds of point of closest approach, but also begins much earlier. The interrogation rates required to achieve these tracks are seen (in Table 3-3) to be not excessive. While the nominal interrogation rate is 1 per second for an aircraft in track at short range, the actual rate is

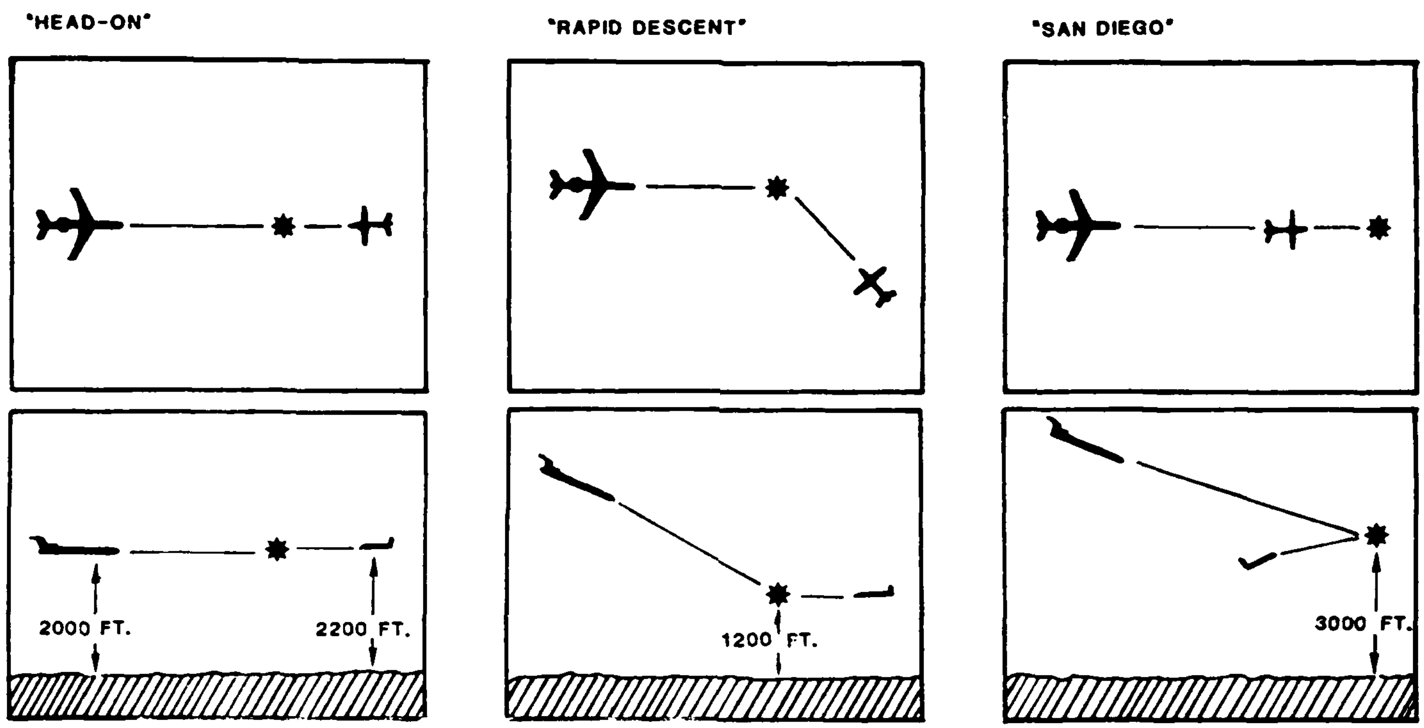


Fig. 3-16. Flight paths in diversity experiments.

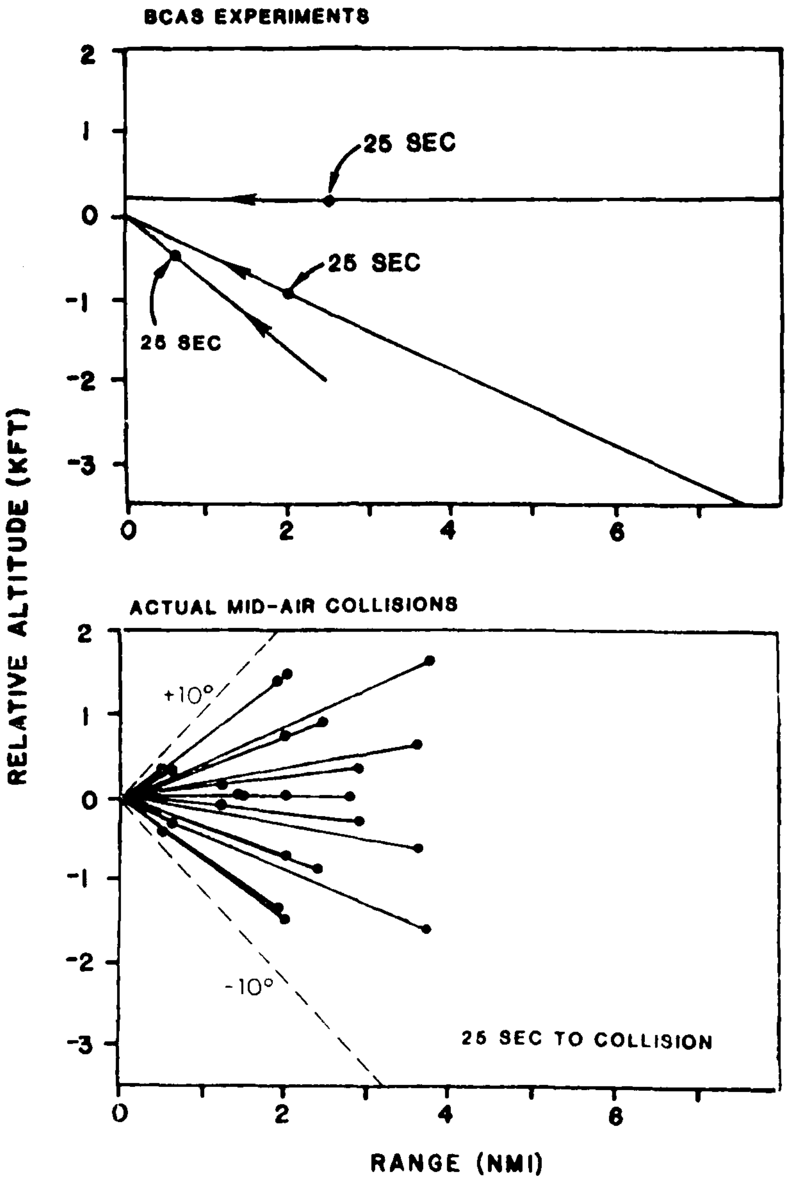


Fig. 3-17. Conditions under which BCAS is being tested.

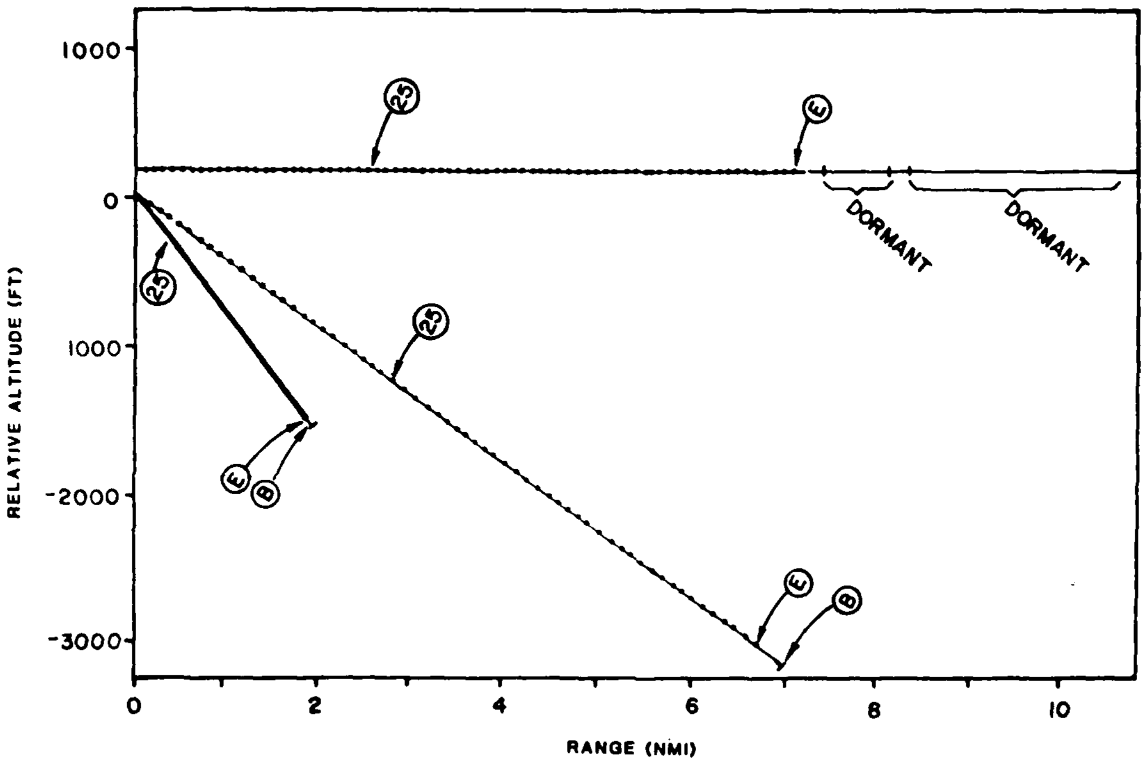


Fig. 3-18. BCAS performance: DABS diversity transponder.

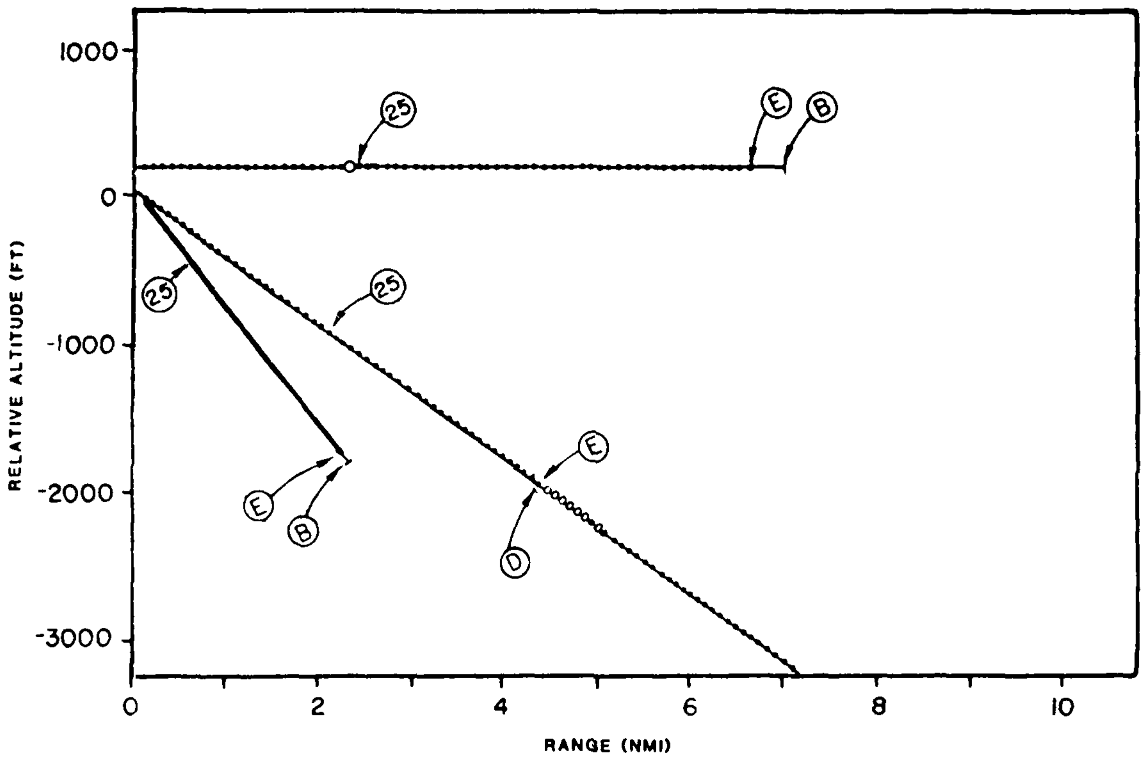


Fig. 3-19. BCAS performance: DABS transponder without diversity.

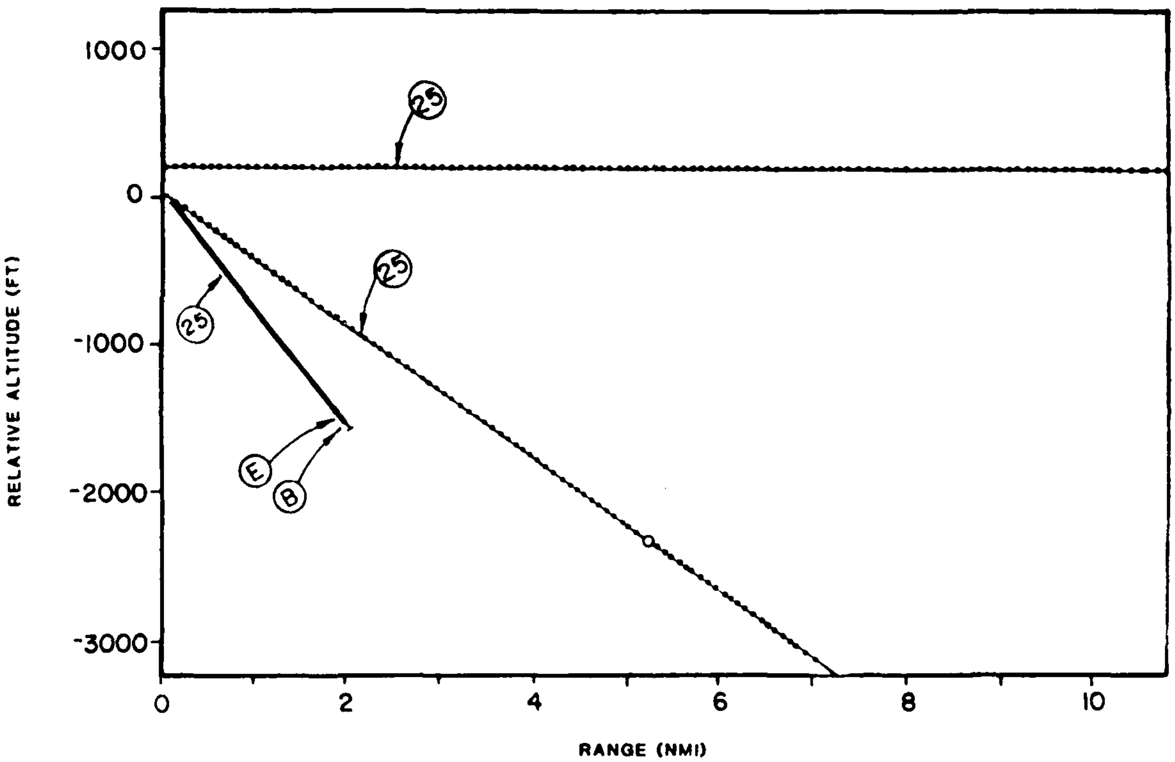


Fig. 3-20. BCAS performance: ATCRBS transponder (without diversity).

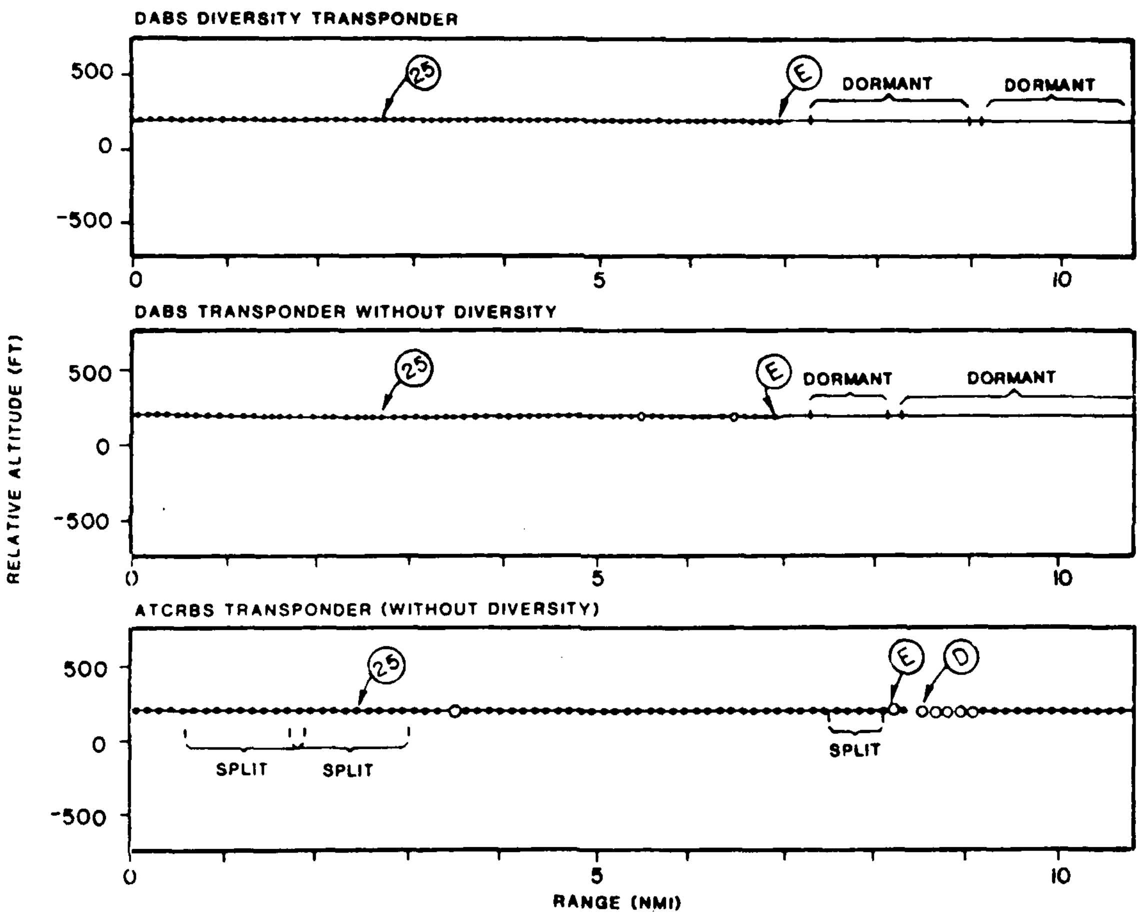


Fig. 3-21. BCAS performance: head-on encounters over ocean.

TABLE 3-3.

DABS INTERROGATION RATES DURING SIX EXPERIMENTS FLOWN OVER LAND

		Interrogation Rate (per sec.)				
		0 to 2 nmi	2 to 4 nmi	4 to 6 nmi	6 to 8 nmi	8 to 10 nmi
DABS transponder with diversity	head-on	1.3	1.2	1.2	0.6	0.2
	rapid descent	1.1	1.1	1.0	NA	NA
	San Diego	1.1	NA	NA	NA	NA
DABS transponder without diversity	head-on	1.0	1.9	1.2	0.6	NA
	rapid descent	1.1	1.0	2.0	0.8	0.3
	San Diego	1.1	NA	NA	NA	NA

NA denotes "not available". Interrogation rate value was not obtained because the experiment was not conducted throughout this range interval.

expected to be higher, because of the need for occasional reinterrogation. These results show an average of about 1.2 per second for tracking within 6 nmi. At longer ranges, the expected interrogation rate is much less, since dormancy is used instead of continuous tracking. The results in Table 3-3 are consistent with this expectation.

In the case of DABS-without-diversity, tracking performance was excellent, having only one coast in all four encounters in the 25 seconds before PCA, and providing clear tracks many seconds earlier. The only flaw of possible significance is a 6-second break in the sequence of target reports occurring about 50 sec. before PCA in the rapid descent encounter. The DABS interrogation rate was somewhat higher in this case as compared with the diversity case.

In the encounters with an ATCRBS transponder, tracking performance was also perfect over the last 25 sec of each encounter and many seconds earlier. In the ATCRBS mode. the incidence of false tracks is also important. During the three experiments over land no false tracks were produced. During the head-on encounter over water there were several false tracks of a type called "range splits" in which the false track was at the same altitude as a real track and at slightly greater range. There were three range splits accompanying the real track that corresponds to the Bonanza aircraft. Fig. 3-21 is marked to show where these occurred. During this experiment, there happened to be one other aircraft in the vicinity, which was tracked by BCAS, and this real track was also accompanied by several range splits. At a later point in the program, a design feature was added that eliminates most of these range splits (see Sec. 3.3.6).

The 12 encounters examined in this section form a subset of a larger series of similar encounters involving a number of different aircraft types. The results of this series of experiments are summarized in the next section.

3.2.4.3 Summary of Diversity Experiment Series

A total of 36 encounters with DABS diversity transponders, 48 encounters with DABS transponders without diversity, and 34 encounters with ATCRBS transponders have been analyzed. These encounters involved the following aircraft types: Boeing 727, Convair 580, Cessna 421, Cessna 172, Beech Bonanza, and Piper Cherokee. As in 3.2.4.2, these tests were performed under severe conditions for BCAS performance, i.e. at low altitudes and in geometries that emphasized look-down angles. In all cases. the BCAS aircraft is equipped with both top-and bottom-mounted antennas.

3.2.4.3.1 Results

The results are shown in Figs. 3-22, 3-23, and 3-24. These figures summarize the target report history during the 50-second period just prior to closest approach. "Target reports" are the final output of the surveillance function of BCAS. The symbols in these figures denote the following events.

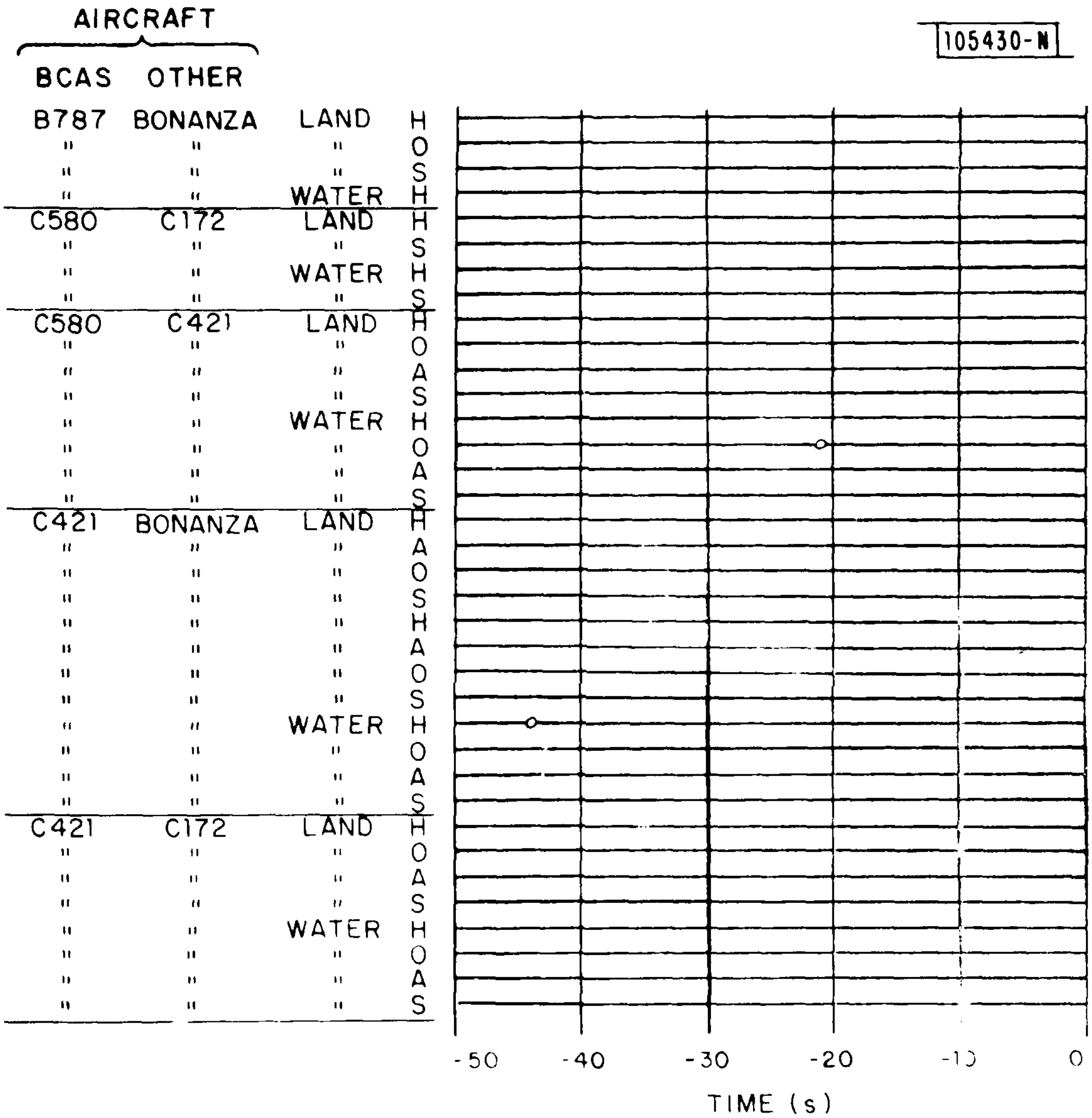


Fig. 3-22. Results of 36 encounters - DABS diversity transponder.

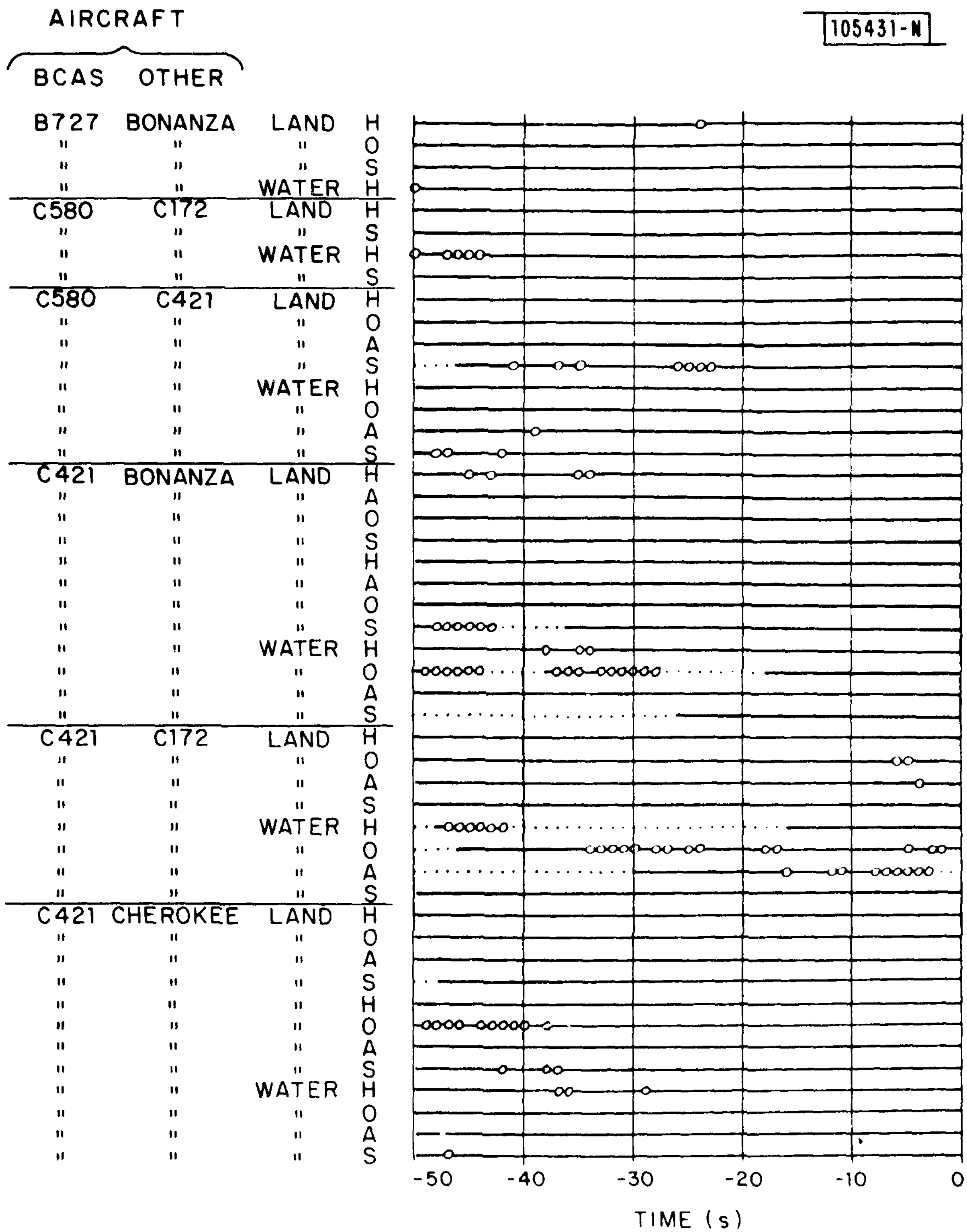


Fig. 3-23. Results of 48 encounters - DABS transponder without diversity.

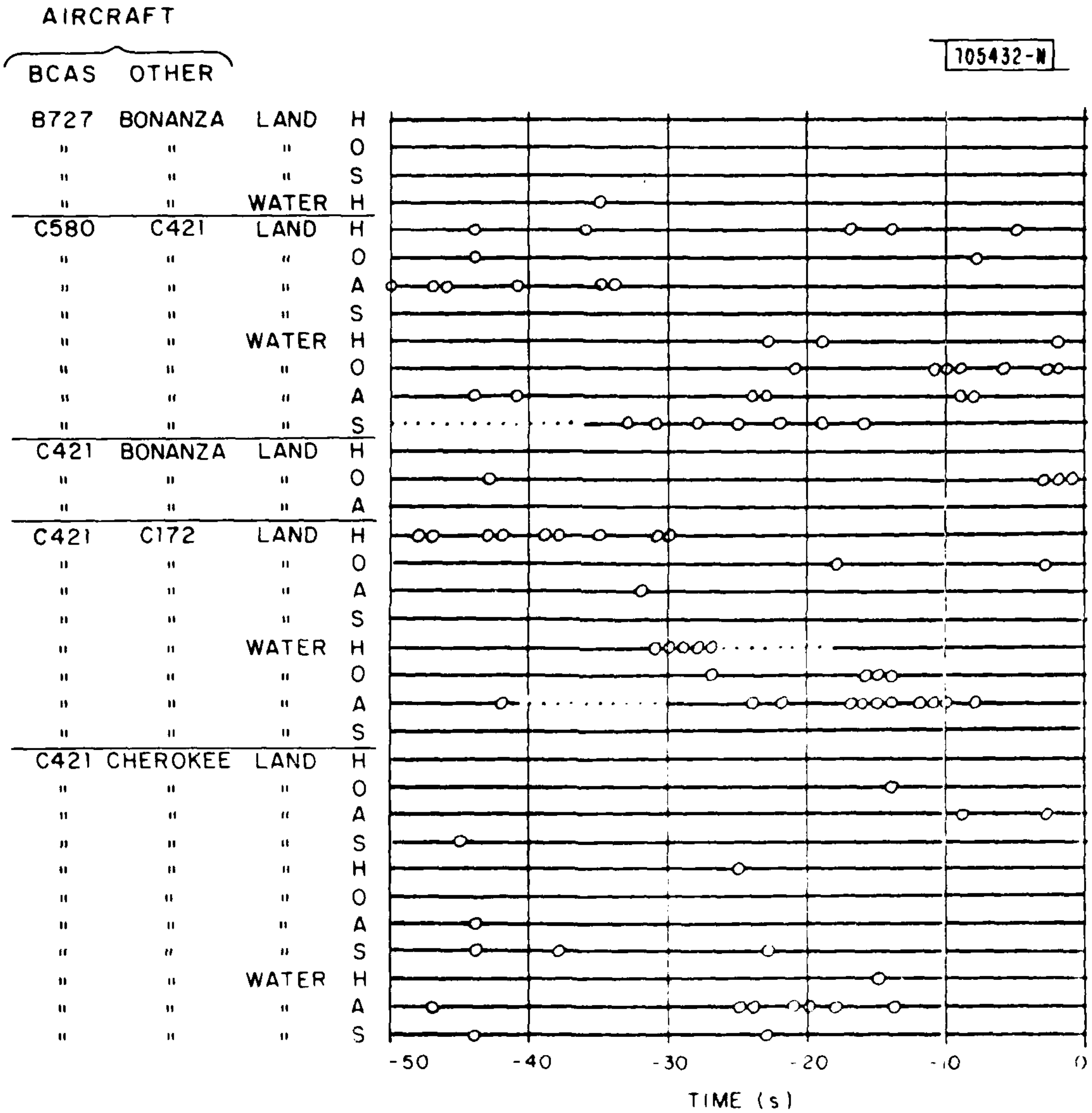
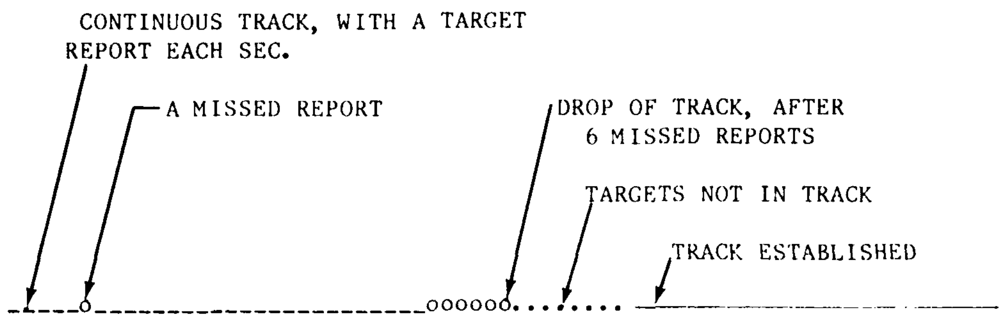


Fig. 3-24. Results of 34 encounters - ATCRBS transponder (without diversity).



Markings on the left side of the figures indicate which aircraft were involved in each encounter. whether the flight was over land or ocean, whether the encounter geometry was head-on (H), obtuse angle (O), acute angle (A), or patterned after the San Diego collision (S). The encounter geometry called "obtuse angle" is the same as the rapid descent encounter shown in Fig. 3-16. When seen from above the paths of the converging aircraft form an obtuse angle of about 135°. The encounter geometry called "acute angle" is the same except that this angle is an acute angle of about 45°.

A statistical summary of these results is given in Table 3-4, according to figures of merit defined as follows:

Successful Tracks. Of the encounters in the data base, this figure is the percentage for which a track existed at 25 seconds prior to closest approach and continued uninterrupted through closest approach.

Track Continuity. Of the time period shown (50 sec. times the number of encounters), this figure is the percentage of the time during which a track existed (including coasts).

Blip/Scan Ratio. With attention limited to the 50-second periods shown, and further limited to the periods in which the target is in track, this figure is the percentage of the scans for which target reports were generated.

False Target Rate. One type of false track in the ATCRBS mode is a range split (see 3.2.4.2.1), often due simply to discrete multipath echoes. Although in most cases these false tracks are eliminated by ATCRBS surveillance processing (see 3.3.6) it was not possible in these AMF tests to implement that multipath track elimination feature because own altitude is not available in the AMF data. As a result many range splits were produced in this data, most of which would probably have not been produced in a real airborne BCAS unit. These were not counted in forming the statistical summary. The false track rate in Table 3-4 includes only false tracks with false altitudes.

TABLE 3-4.

SURVEILLANCE SUMMARY: EXPERIMENTS IN SEVERE GEOMETRIES

	DABS Diversity 36 Encounters	DABS W/O Diversity 48 Encounters	ATCRBS 34 Encounters
Tracks of Real Aircraft			
Successful Tracks (%)	100	94	97
Track Continuity (%)	100	96	98
Blip/Scan Ratio (%)	>99	96	94
False Tracks			
Rate (Per Hour)	0	0	5

3.2.4.4 Significance of Results

When tracking a DABS diversity transponder, the system achieved essentially perfect performance (Fig. 3-22). Single coasts do appear at two separate points, but otherwise, target reports were issued regularly once per second throughout the 50 second duration of all 36 encounters.

In the DABS mode without diversity (Fig. 3-23) performance is seen to be good throughout most of the encounters, however, with definite degradations in some cases. For example, in the head-on encounter over water, between the Cessna 421 and the Cessna 172, the track was established at T = -48 sec., yet it could not be maintained, and it was dropped after 6 coasts. Then, during the next 25 seconds, all attempts to reacquire the track were unsuccessful, so that during this time, no surveillance data was being issued to the threat logic function, and no BCAS alarm could be generated. Finally the track was re-established at T = -16 sec., and thereafter it continued perfectly through T=0. In this case, the result of the surveillance degradation would be a delayed alarm, occurring 16 seconds prior to closest approach.

There is some correlation between performance and whether the flight is over land or ocean, with performance being generally worse when the sea is very calm.

ATCRBS mode results (without antenna diversity), in Fig. 3-24, are similar to the DABS results without diversity. There are occasional coasts and several track drops. The ATCRBS and DABS modes differ more significantly in the incidence of false tracks. While it is essentially impossible to generate a false track in the DABS mode, false tracks do occur at a low rate in the ATCRBS mode --about 5 false altitude tracks per hour in this data. Since false tracks can be at any altitude, only rarely will they produce false alarms. None of the false tracks in this data would have resulted in a false alarm.

The performance shown in Figs. 3-23 and 3-24 was good most of the time in most of the encounters. The statistical summary in Table 3-4 shows that, for example, the DABS transponder without diversity was in track 96% of the time. It is emphasized that worst-case conditions have been focused upon in these DABS experiments in order to be sure that the performance of the DABS mode when operational in the future will be at least as good as the test results.

3.3 ATCRBS Surveillance

The ATCRBS surveillance algorithm* makes use of a number of new techniques to reduce or eliminate the effects of fades, multipath and synchronous garble. This section provides the results of experiments designed to validate these techniques.

3.3.1. Multipath Interference

3.3.1.1 Interrogation Link

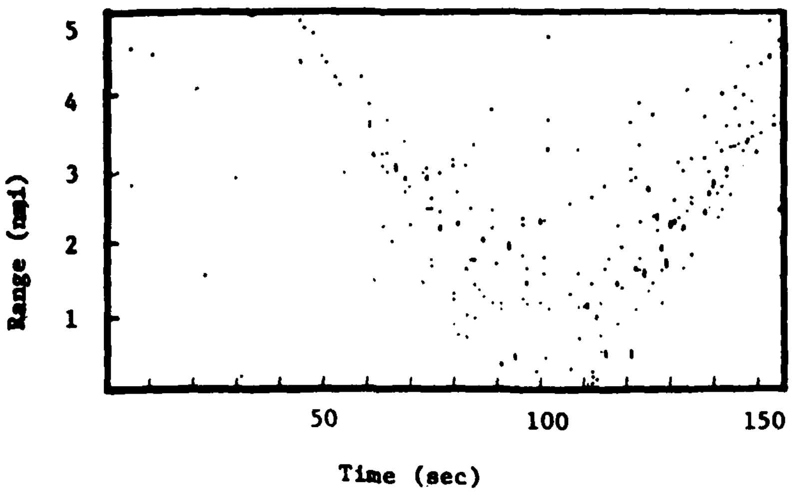
Multipath signals generated by the scattering of mode C P1 interrogation pulses can interact with the interrogation such that a transponder decodes the combination of interrogation and multipath as a mode A interrogation if P1 is delayed 8 μsec, or as a suppression if P1 is delayed 2 μsec. This phenomenon is referred to as "mode conversion". A technique which involves varying the interrogation power has been developed to overcome this interference.

The rationale for varying the interrogation power as a means of overcoming multipath interference on the interrogation link is the fact that in most cases the signal-to-multipath ratio is high, and therefore reducing the interrogation power can reduce the multipath strength to a level below the transponder MTL while maintaining adequate interrogation signal strength.

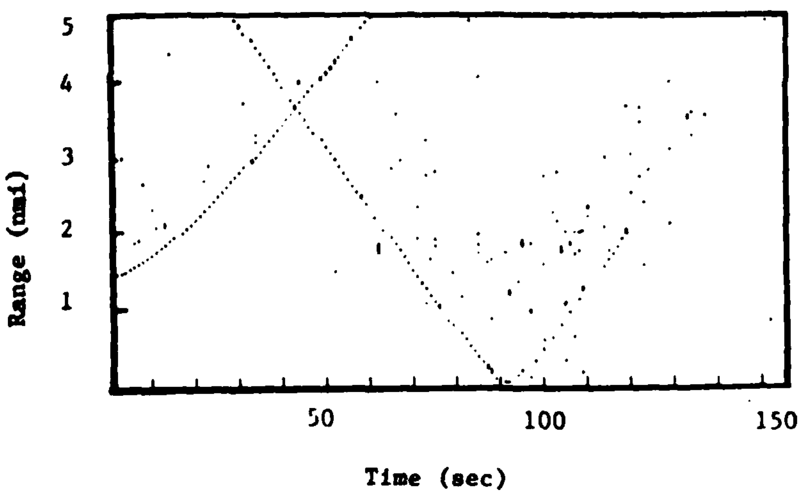
Fig. 3-25 shows data taken from head-on encounters over a land surface. The encounters involved a Cessna 421 at an altitude of 8500 feet and a Convair 580 at 7000 feet. Independent surveillance data obtained with the Lincoln Laboratory DABS Experimental Facility indicated that the encounter in Fig. 3-25a was not a perfect overpass but had a maximum look-down angle from the BCAS aircraft of ~30°. The encounter in Fig. 3-25b was a direct overpass. The figures illustrate the improvement in range information reliabilty at close range on the bottom-to-bottom antenna link as interrogation power was changed between encounters. Throughout the encounter in Fig. 3-25a, mode C interrogations were transmitted using full power (500W at the AMF transmitter rf port). The power was reduced by ~6 dB for the encounter shown in Fig. 3-25b. The desired range track became more reliable and the number of extraneous replies was reduced. Thus reducing interrogation power has improved surveillance performance and reduced the likelihood of false track initiation.

To further understand the effect of power programming, experimental equipment was modified so that further measurements of these effects might be made in a precisely controlled way.

*Original ATCRBS surveillance algorithms are described in MITRE MTR-7280, August 1976. The modifications described in this paper are documented in a report to be published in early 1981.



a. Full Power Interrogations



b. Reduced Power Interrogations

Fig. 3-25. Interrogation link performance across bottom-to-bottom antenna link over land surface (geometry not identical on successive flights).

3.3.1.1.1 Hardware Modifications

In the original experiments, interrogation power could only be varied manually. It was held constant for the duration of an encounter (several minutes), and then changed to a new value and held constant while the encounter was repeated. All conditions were duplicated as accurately as possible. However it was not possible to repeat multipath conditions exactly, and of course encounters with targets of opportunity were not repeatable at all.

A high speed. digitally controllable attenuator was added to the equipment so that it was possible to program a sequence of several power levels over a very short period. The need to repeat encounters was eliminated since within one encounter, measurements could be made at each of several interrogation power levels.

3.3.1.1.2 Results

With this new capability, air-to-air measurements were made during a number of encounters. Relative target altitude was varied from -500 to -3000 ft. In some cases the Cessna 421 was the BCAS aircraft and the Beech Bonanza was the target. In other cases the larger Convair 580 was the BCAS aircraft while the Cessna 421 was the target. As an example, the results from one of these encounters (Experiment 847H) are given in Fig. 3-26. This was a head-on encounter. The BCAS aircraft. the Convair, was at 5 00 ft. and the target, the Cessna -- equipped with a single bottom mounted antenna -- was at [illegible] ft. The encounter was flown over land. The interrogation power was about 250 watts referred to the antenna. The reduced power levels were -6, -12, and -18 dB relative to full power. Figure 3-26 shows the output of the reply processor. Bottom antenna receptions are shown. Each detected reply is represented as one dot. (The reply processing includes dynamic thresholding (see 3.3.1.2.1) and phantom elimination (3.3.4).

Fig. 3-26 shows that at short range, the full-power bottom-antenna interrogations become unreliable. The reduced power interrogations however are seen to provide significantly better performance in these situations.

In summary. power programming has been found to be useful in improving ATCRBS-mode link reliability. particularly for the BCAS bottom antenna. and in cases where the target is located at a significant look-down angle. This supports the inclusion of a power programming sequence (or a whisper-shout sequence (3.3.2) that achieves the same benefits) in the BCAS design for high performance aircraft.

3.3.1.2 Reply Link

Reply data indicates that ground-bounce multipath also causes severe reply garbling of signals received on the bottom antenna at close ranges. Two techniques to overcome the effect of multipath were evaluated. The first was

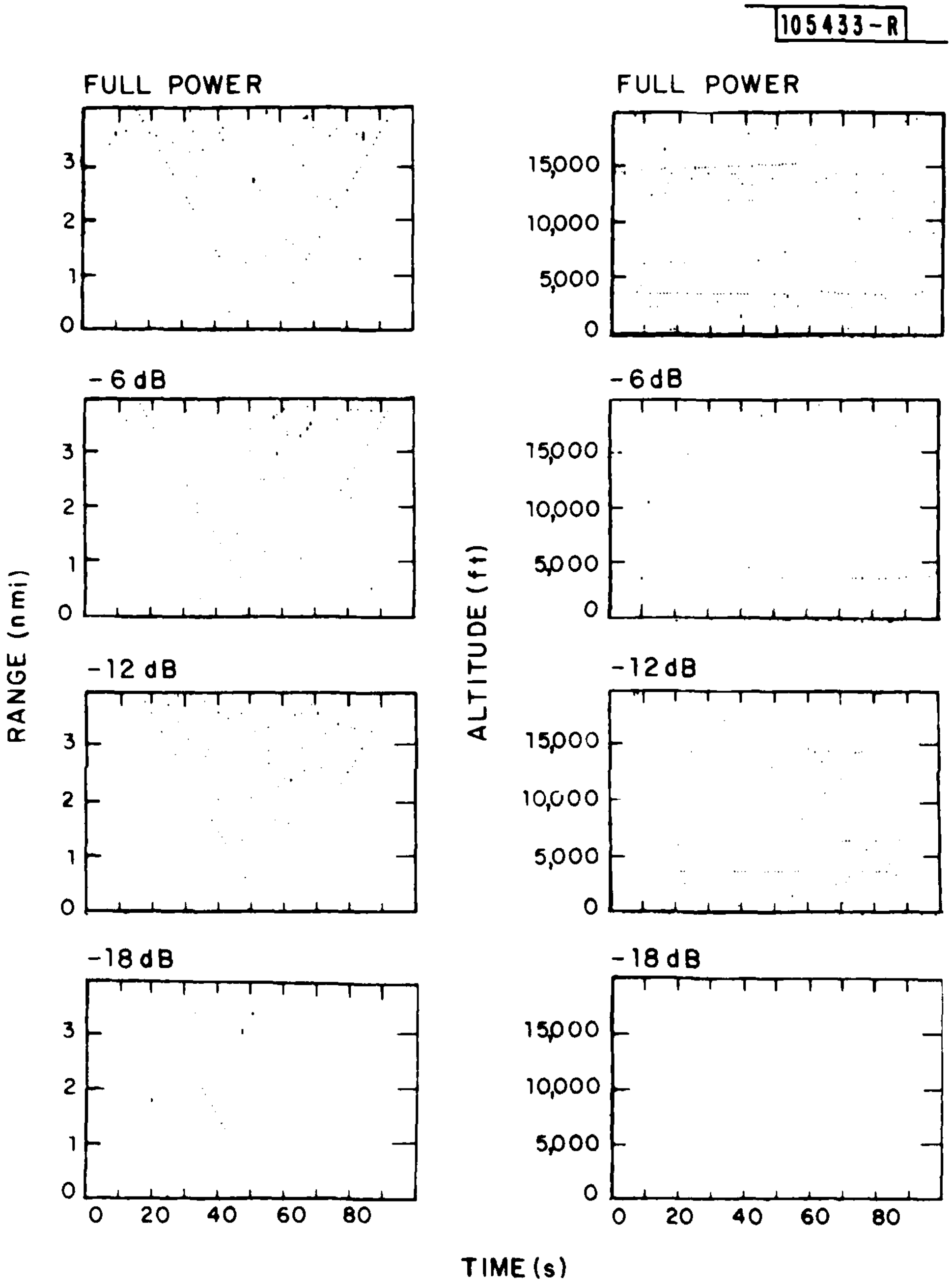


Fig. 3-26. Improvements due to power programming.

dynamic thresholding in the BCAS receiver pulse detection circuitry. The second was the use of a more sophisticated ATCRBS reply processor than has been used in the past.

3.3.1.2.1 Dynamic Thresholding

Observation of log video signals during flight encounters indicated that the signal-to-multipath ratio is often reasonably high (>10 dB), even at close range. Thus an adaptive or dynamic MTL (DMTL) can be used to effectively prevent the BCAS receiver from detecting low level multipath signals. The concept is illustrated in Fig. 3-27 with a fixed threshold. Multipath stronger than the MTL can be interpreted as valid reply pulses by the receiver. If the MTL is raised to some DMTL value not far below the F1 pulse (first framing pulse), the multipath will not be detected. In the experimental circuit tested, DMTL was set 6 dB below the pulse which triggers it.

Without DMTL, the multipath signal trailing the last pulse of a close range reply gives rise to multiple overlapping bracket detections. Fig. 3-28 is a series of computer printouts of bracket detection data illustrating the data quality improvement due to DMTL. The vertical axis represents range in time units of 0.120 microseconds. The horizontal axis represents the relative time of each interrogation as the flight proceeds. The range of the aircraft bracket track shown varies from 2.0 nmi to 0.5 nmi. The detected aircraft was at a lower altitude than the BCAS aircraft. The link reliability was low on the top BCAS antenna starting at time 2550 regardless of whether a mode C interrogation was transmitted as in Fig. 3-28a or a mode A interrogation as in Fig. 3-31d. (Mode A interrogations result in a different reply pulse set which generates a different multipath response than the mode C interrogations.)

Mode C interrogations from the bottom antenna resulted in a poor track when DMTL was not used as indicated in Fig. 3-28b. However as indicated in Fig. 3-31c the use of DMTL significantly improved bracket detectability. A number of mode C to mode A interrogation mode conversions may be noted (see 3.3.1.1). As shown in Fig. 3-28e, when DMTL was not used, multiple overlapping bracket pairs were consistently detected. Fig. 3-28f shows that DMTL was successful in eliminating many of the false brackets due to multipath.

Fig. 3-29 shows reply pulse data processed with and without DMTL. Parallel lines correspond to bracket pulses and altitude code pulses associated with BCAS replies; while random dots are primarily multipath signals. For ranges less than 5 nmi the multipath environment on this bottom-to-bottom antenna link was very intense. The figure illustrates several features of DMTL performance. In comparing the pulse data in Figs. 3-29a and 3-29b it is seen that for the time period from 10 to 105 seconds, many extraneous multipath pulses were eliminated by the DMTL, resulting in improved altitude information reliability as shown in Figs. 3-29c and 3-29d. As the aircraft separated after crossover the signal-to-multipath ratio decreased reducing the effectiveness of DMTL as shown by the reappearance of multipath pulses (and mode conversions) in Fig. 3-29b for the time period beyond 105 seconds.

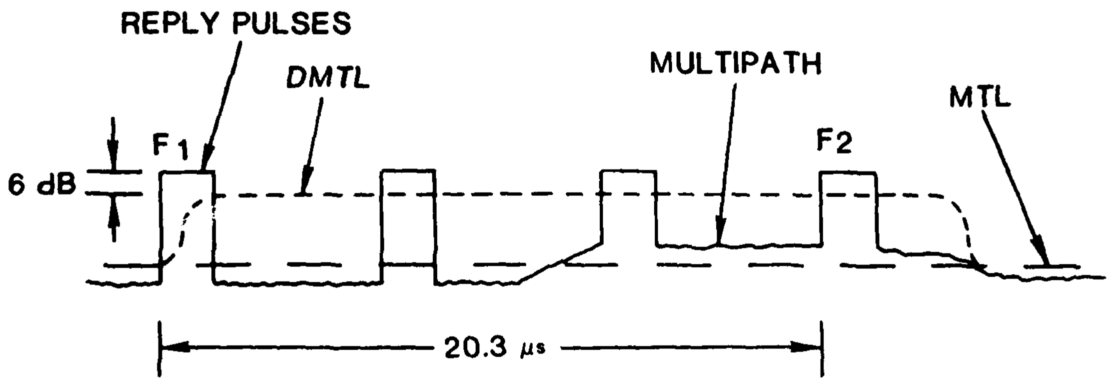


Fig. 3-27. Dynamic MTL.

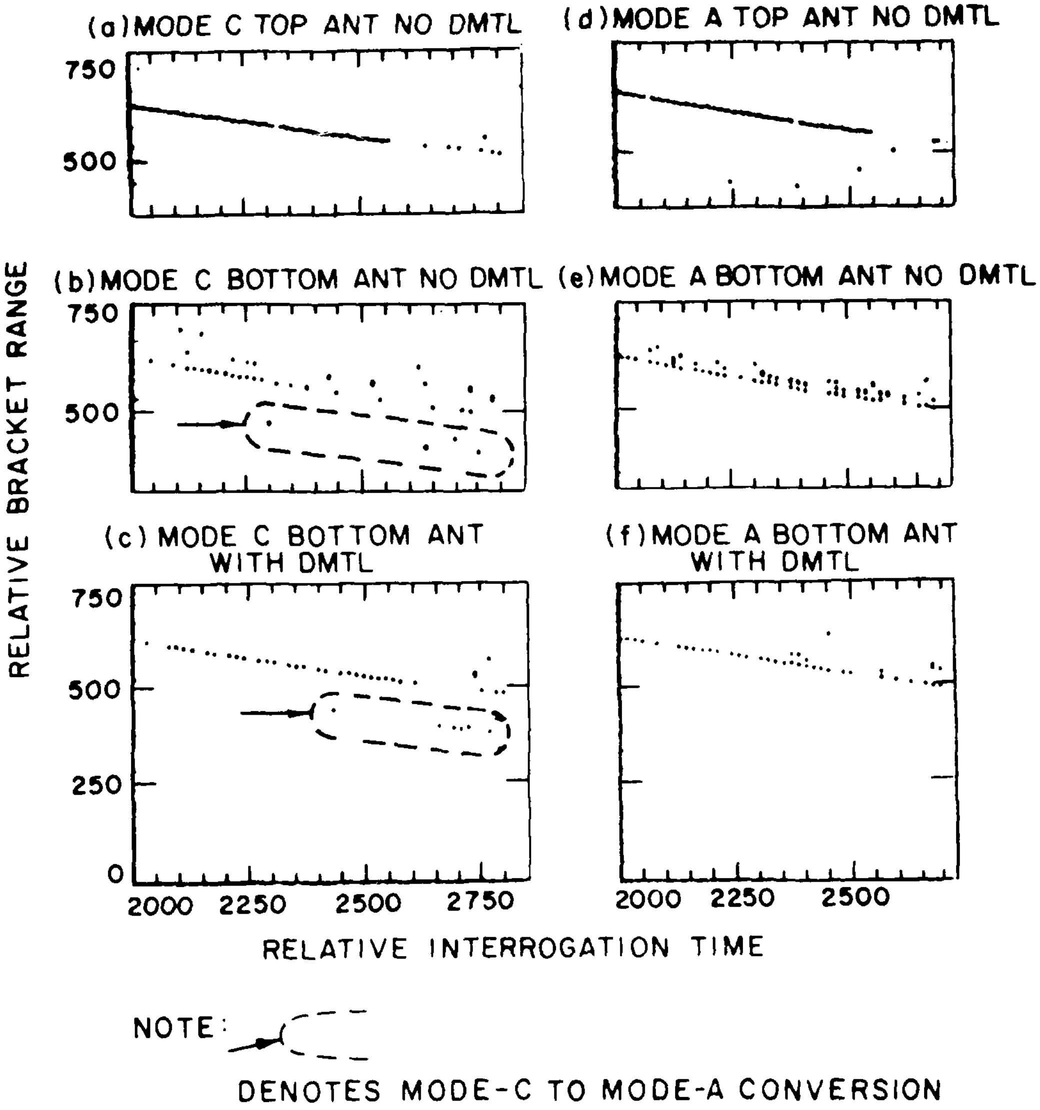


Fig. 3-28. Effect of DMTL on bracket detection.

Note: BCAS operating on bottom antenna.

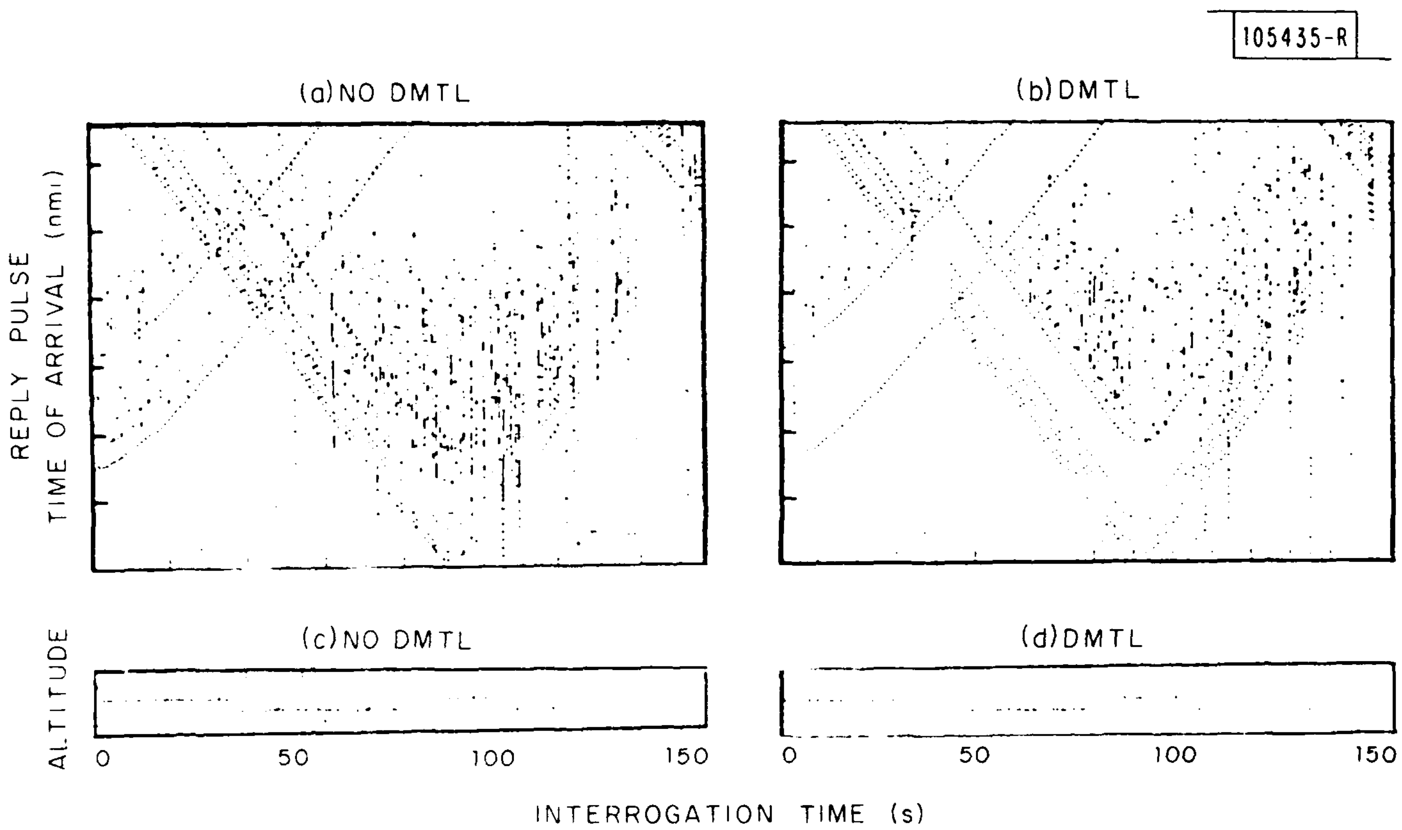


Fig. 3-29. Effect of DMTL.

Another feature illustrated in Fig. 3-29b is a threshold "capture" effect indicated by the loss of pulses occurring between times 33 and 43. This phenomenon occurs whenever two replies overlap and there is enough difference in signal strengths that DMTL eliminates the weaker signal. This phenomenon reduces the effectiveness of DMTL at greater ranges where there is a higher likelihood of overlapping replies. However the use of a whisper-shout interrogation sequence (see 3.3.2) to break up the set of overlapping replies into a number of sequential subsets of replies with roughly equal signal strengths tends to reduce the probability of reply loss due to threshold capture.

Based on this work, it has been concluded that dynamic thresholding significantly improves the performance of the ATCRBS reply link and that the following characteristics constitute a suitable BCAS design for a dynamic threshold circuit.

- Boxcar threshold waveform of 22 μs duration
- Threshold level -10 dB relative to peak value of triggering pulse
- Retriggerable upward, 5 dB hysteresis*
- Not retriggerable downward
- Narrow pulse rejection (so that pulses with durations less than 200 ns do not trigger DMTL)

3.3.2. Whisper-Shout

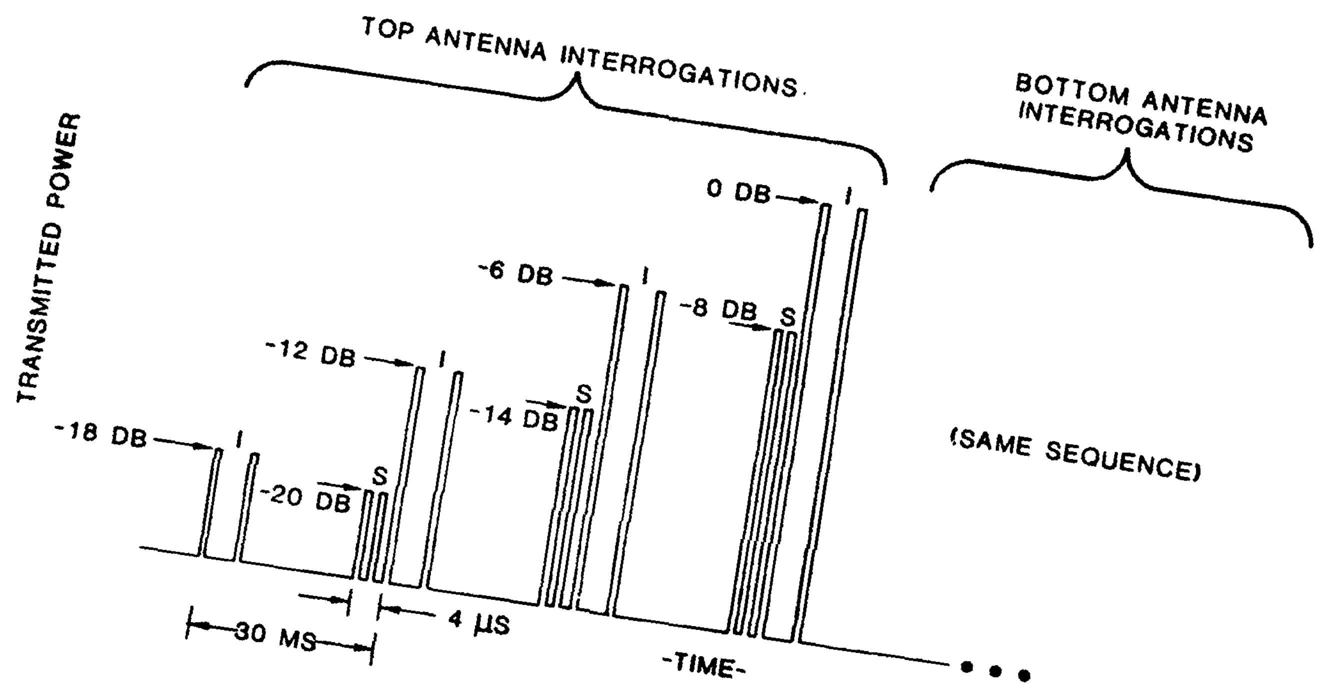
In conjunction with the experiments on power programming described above, whisper-shout experiments were also conducted. Whisper-shout, a technique invented by the MITRE Corp., employs a sequence of interrogations beginning at a low power and ending with full power. Except for the first, these interrogations are preceded by suppressions, the purpose of the combined sequence of interrogations and suppressing being to partition the set of ATCRBS replies so that the number of reply overlaps is reduced, while each reply is nevertheless received at some step in the sequence.

In its original form whisper-shout was used on the top BCAS antenna, together with a single interrogation on the bottom antenna. Whisper-shout is now also being used on the bottom antenna as a way of obtaining the same benefits as power programming.

3.3.2.1 Experimental Conditions

Most of the recent experiments employed a sequence of 4 top and 4 bottom interrogations, in 6-dB steps, and interspersed with suppressions offset by 2 dB. This whisper-shout sequence is illustrated in Fig. 3-30.

*Hysteresis implies that a pulse occurring during the 22 μs DMTL period must be 5 dB stronger than the original triggering pulse in order to cause further upward triggering.



NOTE: THESE EXPERIMENTS DO NOT EMPLOY THE P4 PULSE OF A STANDARD ATCRBS MODE BCAS INTERROGATION. THE P4 PULSE IS OMITTED SO THAT A DABS TRANSPONDER CAN BE USED FOR ATCRBS EXPERIMENTATION.

Fig. 3-30. Whisper/shout sequence.

Several other sequences were also tried, but these were judged to be less effective. Although not optimum, the 4 top and 4 bottom sequence has been adopted as a baseline design.

3.3.2.2 Results

A large number of whisper-shout air-to-air measurements have been conducted. These results indicate that whisper-shout achieves a significant and consistent improvement, both in reduction of synchronous garble and in alleviation of ground-bounce multipath effects.

Typical results are given in Figs. 3-31, 32, 33, and 34. Figures 3-31 and 3-32 resulted from a controlled encounter (experiment 847E) between the Convair 580 (the BCAS aircraft), and a Cessna 421 (the ATCRBS target) equipped with only a bottom antenna. The encounter was head-on with 1500 feet altitude separation. These are essentially the same conditions as in the power programming experiment discussed above in connection with Fig. 3-28. Fig. 3-31 is arranged in a before-and-after format showing on one half of the figure the performance of a single full power interrogation, and on the other half the performance of whisper-shout. The whisper-shout plot shows the composite of all replies in the whisper-shout sequence and does not include replies to the single full-power interrogation. These are bottom antenna results, which might be compared with the power programming results in Fig. 3-28. Like power programming, whisper-shout is seen to significantly improve performance.

An example of the top-antenna performance is given in Figs. 3-33 and 3-34. These data were collected in a higher density of traffic, approximately the maximum specified for active BCAS, which is 0.02 aircraft per square nmi. The traffic consist entirely of targets of opportunity. In this higher density, synchronous garble problems are evident. The results show that whisper-shout does in fact significantly improve performance, both in range and altitude.

3.3.3 Tracker Improvements

A number of tracker modifications were made to improve the quality of tracks on real aircraft and to reduce the occurence of false tracks. These modifications and the resulting performance improvement are described in this section.

The original tracker was designed to operate in high aircraft densities where multiple reply overlaps are common. Its design philosophy can be summarized as follows. Reply overlap corrupts the 12-bit altitude code, mainly by converting 0's (no energy) into 1's (by superposition of pulse energy from an overlapping reply). The resulting hidden 0's are assumed to be exposed in a matter of seconds due to changes in the relative geometry of the aircraft. Therefore, it is reasonable to continuously form and extend tracks and to correct their altitudes as 0's are revealed. By the time a track has existed about 10 to 30 seconds (depending on its range), its altitude can be assumed to be correct, and the track can be passed to the collision avoidance algorithms.

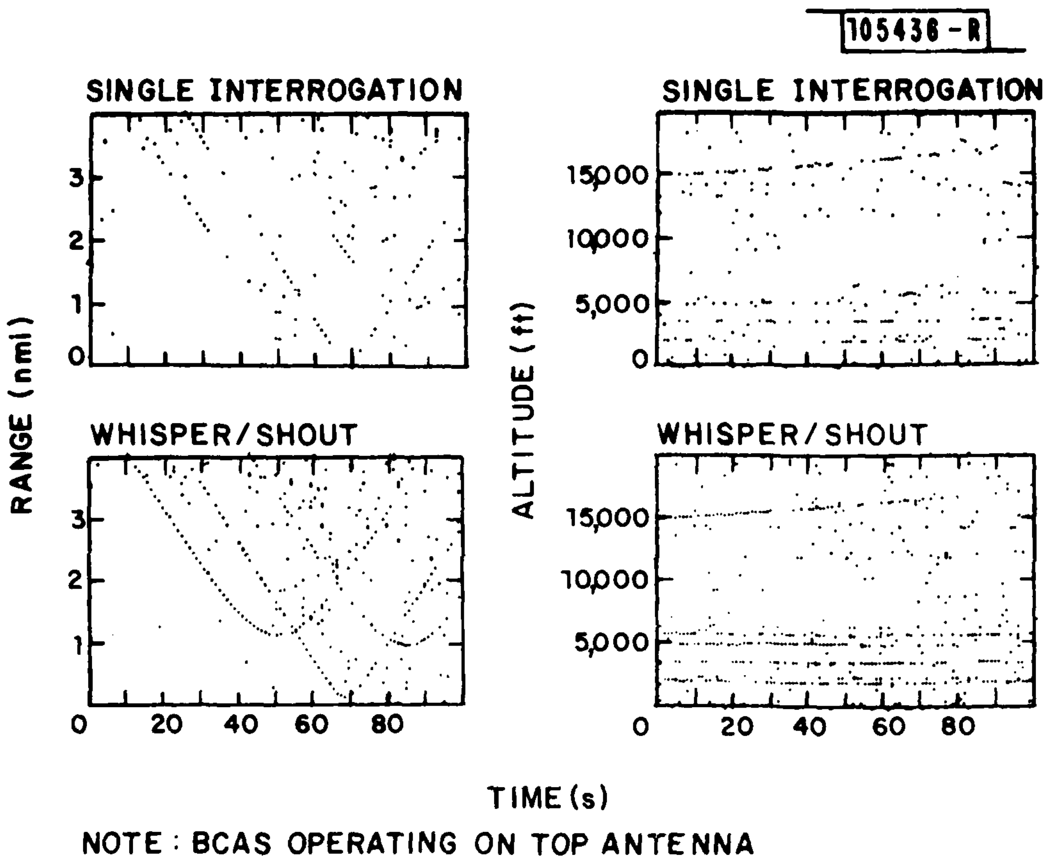


Fig. 3-31. Improvements in multipath tolerance due to whisper/shout.

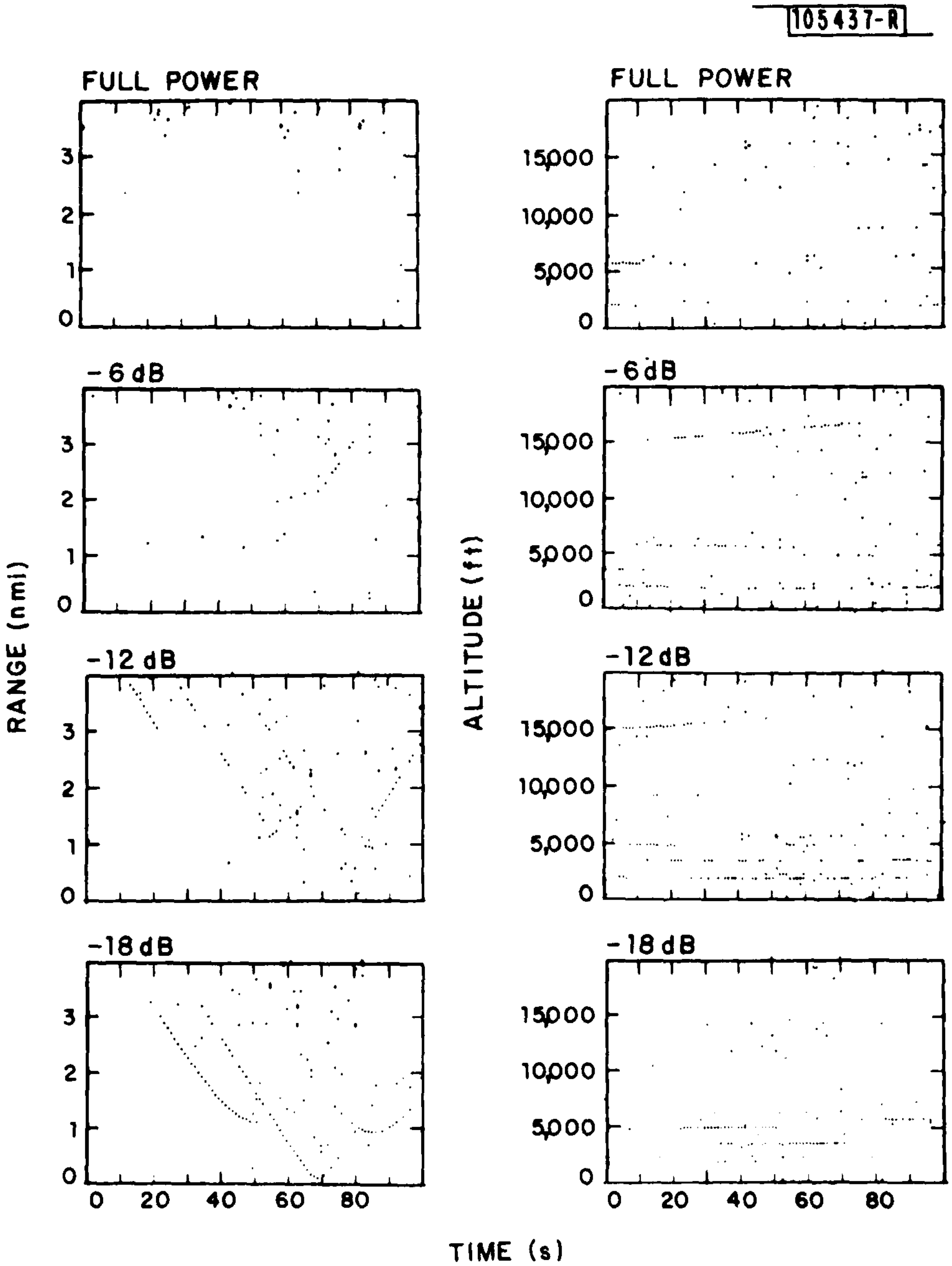
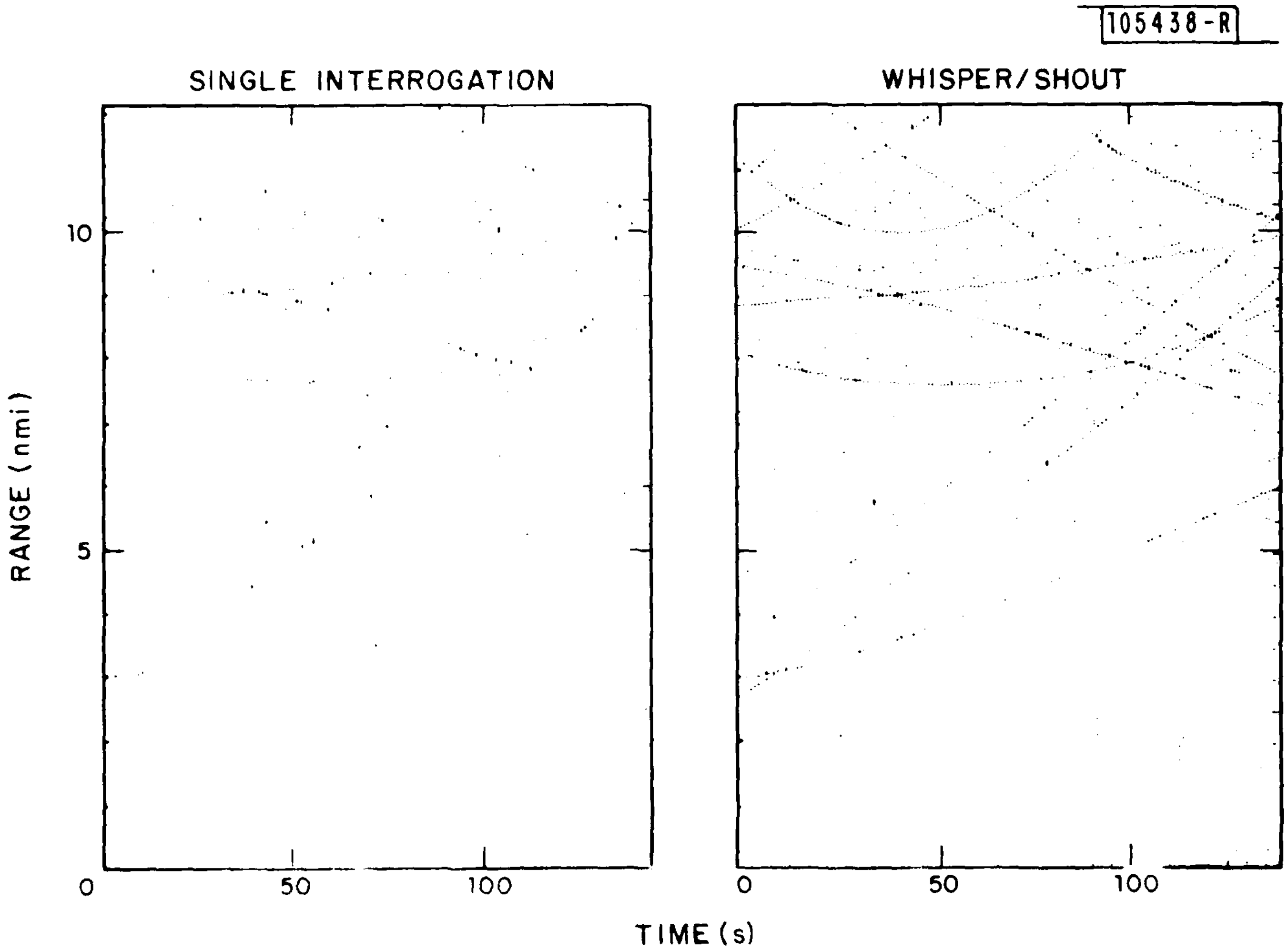


Fig. 3-32. Detailed whisper/shout performance corresponding to Fig. 3-31.



NOTE: BCAS OPERATING ON TOP ANTENNA

Fig. 3-33. Range performance improvement due to whisper/shout.

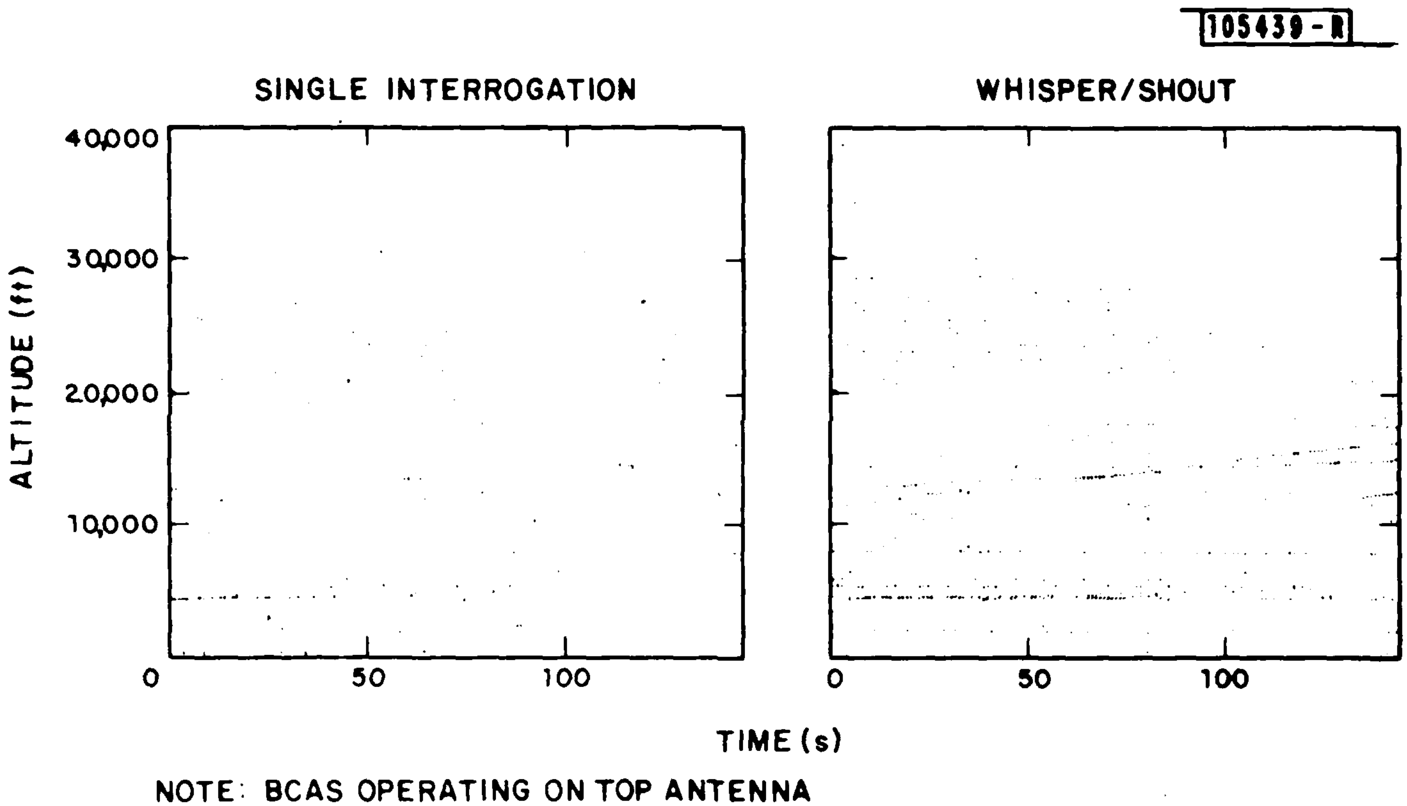


Fig. 3-34. Altitude performance improvement due to whisper/shout.

3.3.3.1 Modifications

Surveillance processing consists of five major tasks. The function of each, its original form, and the modifications made to it are described in the following paragraphs.

3.3.3.1.1 Reply preprocessing

This task combines the replies from the 8 interrogations in one second (4 whisper shout interrogations on the top antenna and 4 on the bottom) into a single set of processed replies. The function retains the best reply of those received from a given aircraft, that is, the reply least likely to have been garbled by the insertion of extra 1's.

No modifications were made to reply preprocessing.

3.3.3.1.2 New-track formation

The original algorithms operated on all processed replies from the previous 4 whisper shout scans (the path shown with a dashed line in Figure 3-35). A new track was formed for each set of 4 replies that lay in a straight line in range. Each bit of the 12-bit track altitude was set to "1" if at least 3 of the 4 replies contained a "1" in a given bit position.

Three modifications were made. First, only replies not used to extend tracks are input to the algorithm. (The path labelled "uncorrelated replies" in Figure 3-35). Second, tentative tracks are formed using only the last 3 scans, instead of 4. Third, the tentative track is kept only if the three reply altitude codes agree in all 8 most significant bits (or in 7 out of 8, and 1 out of 3 of the least significant bits). If agreement is found, the track altitude is set to a best estimate based on the 3 ATCRBS reply codes and their associated confidence bits. The confidence bits are provided by the hardware, and indicate when a code bit may have been corrupted by an overlapping reply.

3.3.3.1.3 Track extension

This task correlates replies from the current scan with previously existing tracks. The first step finds all replies that lie in a range window centered on the predicted track position. Then the altitude of each such reply is compared to the predicted track altitude. The original algorithm extended the track for each reply whose altitude could have been the predicted altitude corrupted by the addition of up to 5 extra "1"s. The track would also have been extended for each reply that had, in one bit position, a 0 where the track prediction had a 1. This extension would have been moved to the predicted altitude corrected by the deletion of the 1 which was not present in the reply.

Several modifications were made. The range tracker gains and correlation window were increased. The altitude window width was increased from ± 100 to ± 200 feet. The track is not extended for corrupted ATCRBS replies, and the track altitude is never corrected by more than 200 ft.

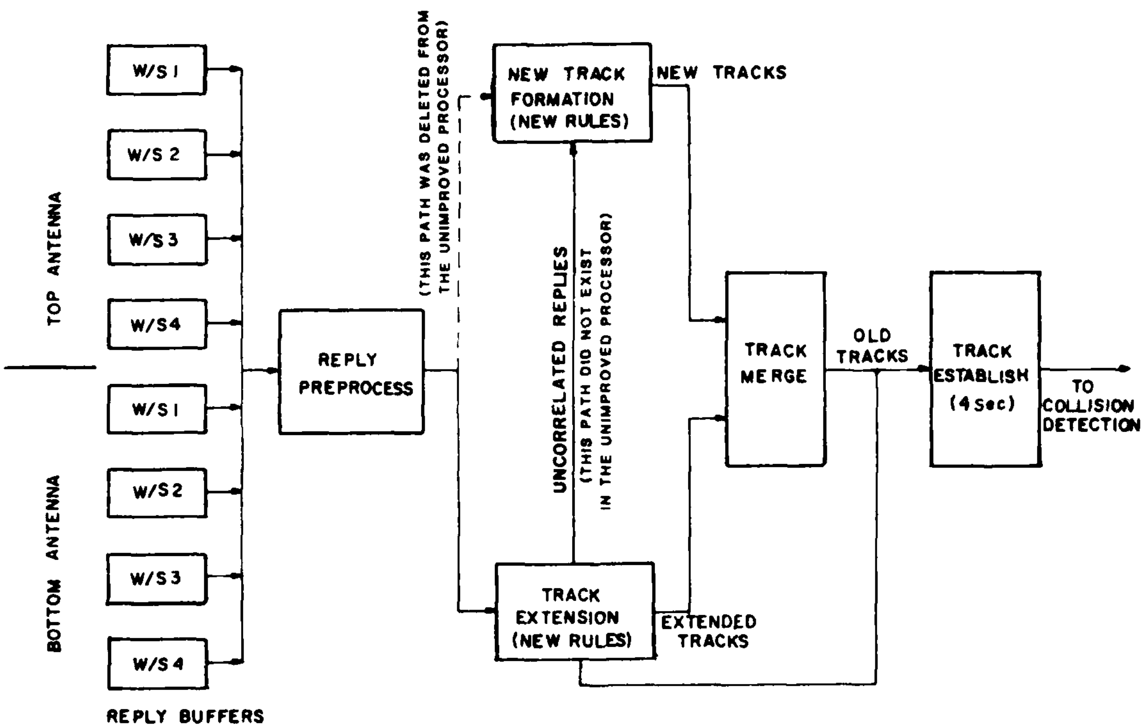


Fig. 3-35. Improved ATCRBS surveillance processing.

3.3.3.1.4 Track merge

This task attempts to eliminate redundant tracks and/or tracks which are probably at the wrong altitude. The multiplicity of tracks formed by the unimproved processor arose from using all replies in new track formation, and from multiple extension of tracks using corrupted replies. Fewer redundant tracks are formed by the improved processor.

The merge function was left unchanged. Some of its logic dealt with altitude corrected tracks, and is no longer applicable.

3.3.3.1.5 Track establishment

The only change to this task was to reduce establishment time to 4 seconds for all tracks, regardless of range.

3.3.3.2 Evaluation of Improvements

The improvements resulting from the the above modifications were evaluated for 36 minutes of reply data at various densities above and below the targeted 0.02 aircraft per square nautical mile. The data base consisted of 10 segments of data recorded in different locations (Boston, New York and between).

The data base was examined manually to identify the reply sequences that were considered to be trackable. The sum of the time durations of all such reply sequences was computed and divided into the sum of all continuous track sequences output by the unimproved and improved surveillance processors. Established tracks existed 81% of the time for the unimproved processor and 92% of the time for the improved processor. The total number of false tracks, normalized to a per hour figure, was 109/hour for the unimproved and 2/hour for the improved.

An additional 3 minutes of data were processed and used to evaluate performance due to various options in the link design and reply processing hardware. The average traffic density within 10 nmi. and including all mode-C aircraft, with or without altitude reporting, is 0.026 per sq. nmi. Figure 3-36 shows the processed replies (output from the reply preprocessing function) when phantoms are eliminated and replies having a zero mode C code are retained. Figure 3-37 shows the manually determined "trackable reply sequences". The sum of all trackable reply sequences is 1586 seconds. Figure 3-38 shows the established tracks formed by the improved processing. The gaps where the processor failed to output a track sum to 71 seconds yielding a 95.5% probability of track. There are no false tracks. The performance of the unimproved processing was significantly worse and was not quantified.

3.3.4 Phantom Elimination

The hardware $F_1 - F_2$ bracket detector and reply processor can be instructed to retain or reject replies whose F_1 and F_2 brackets could have been formed by the code pulses of overlapped replies. Figures 3-36 to 3-38

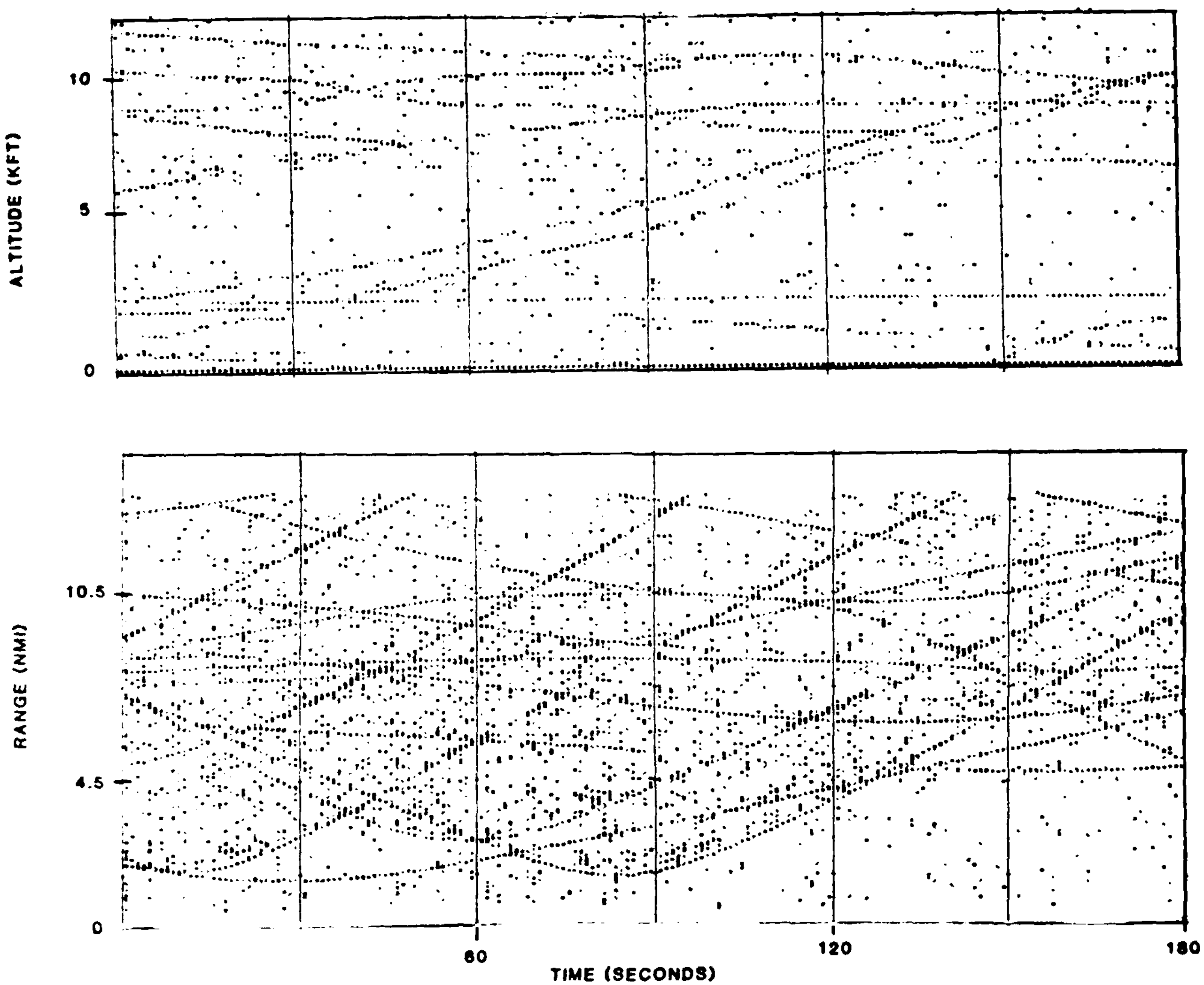


Fig. 3-2[illegible]. Processed replies (phantoms eliminated, non-mode C retained).

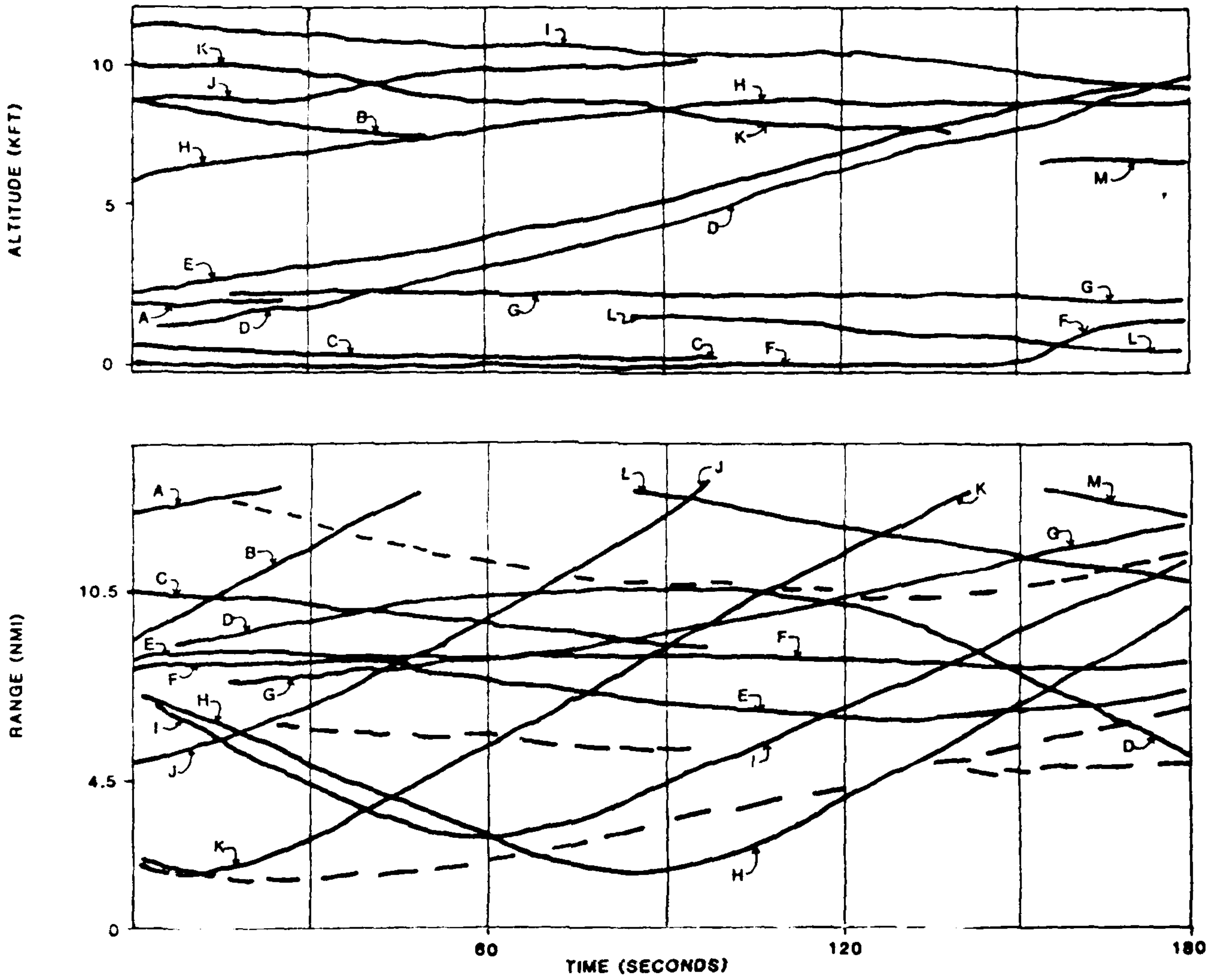


Fig. 3-37. Trackable reply sequences (---is non-mode C).

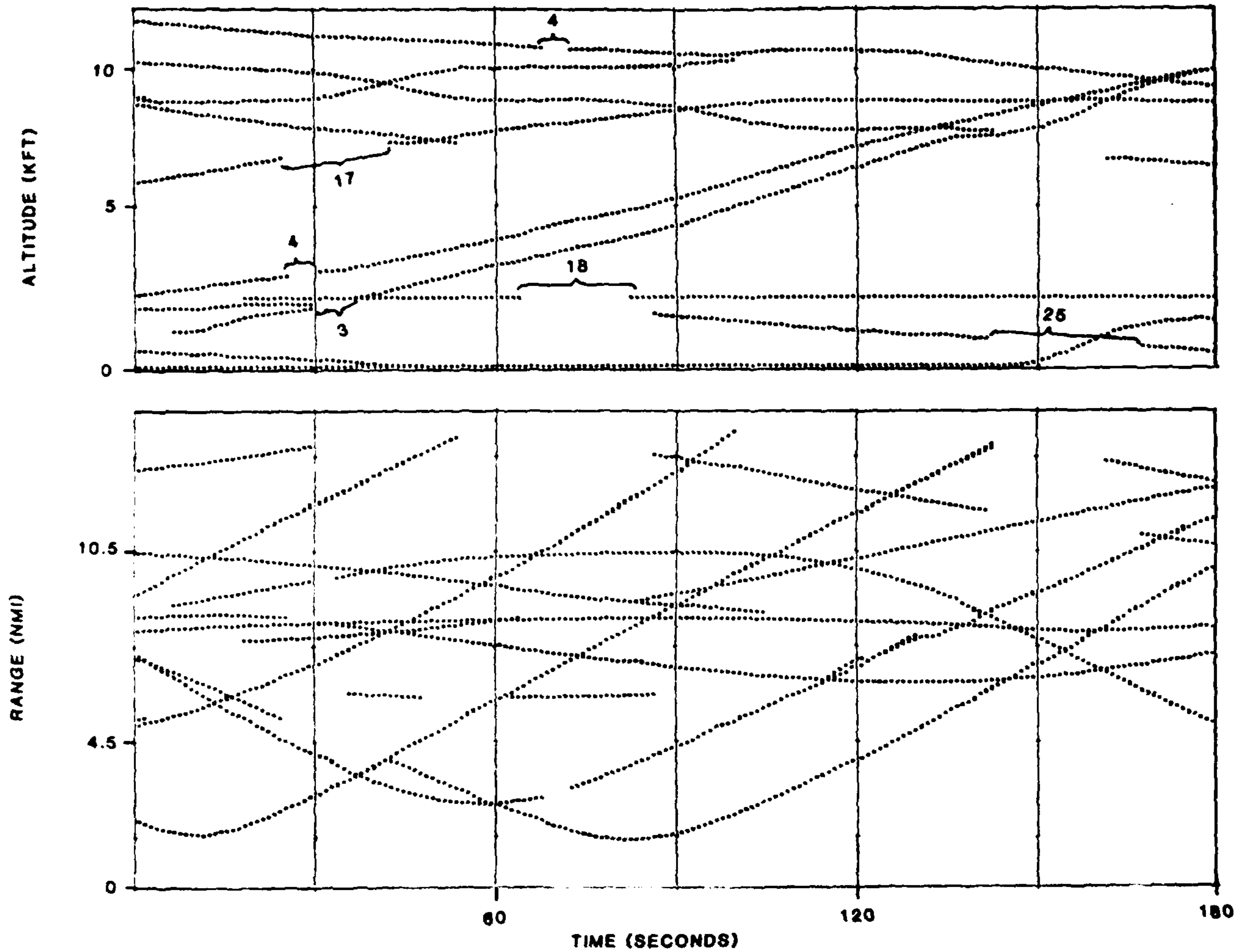


Fig. 3-38. Improved processor tracks.

represent data taken with phantoms eliminated. (The data shown was recorded in pulse form by the Airborne Measurements Facility, and reply processing was implemented in software). Figure 3-39 shows the tracks formed when phantoms were retained. and the track gaps now total 55 seconds, yielding a tracking probability of 96.5%. Note the appearance of 4 tracks not previously observed. Each track corresponds to clearly visible (but not necessarily real) reply sequences in range and altitude in the reply plots (which are not shown here). Track 4 is a false track formed from 12 phantom replies, all at the same altitude. Tracks 1, 2, and 3 are also false. In addition to the 3 minutes of data shown in Fig. 3-39, 7 minutes of replies with phantoms retained were processed and 10 false tracks were observed. None of the 10 appeared in the tracks formed from the replies processed with phantom elimination. The increase in probability of track when phantoms were retained was only about 1%. Phantom elimination was especially helpful in eliminating tracks whose F_1, or F_2 (not both) was due to multipath. While these results, for 10 minutes of data from the Logan airport area, cannot be used to infer that all phantom/multipath tracks will necessarily be eliminated in other flight and terrain conditions, we believe that phantom replies should be eliminated in the BCAS reply processor.

3.3.5. Additional Interrogation Experiments

Following the validation of the tracker improvements, several experiments were conducted to ascertain the impact of eliminating some of the interrogations in the top-bottom whisper-shout sequence. These are described in the following sections.

3.3.5.1 Need for Whisper-Shout with Improved Tracker

The need for whisper-shout is clearly demonstrated in Fig. 3-40, which shows the tracks formed by the improved processor using replies from only the top and bottom high power interrogations. The tracking probability is about 60% and no false targets appear. The altitude tracks are shown as plotted by the computer. The range track plot is augmented by X's showing the missing track segments. The X's, or tracking gaps generally occur in areas of multiple reply overlap. Several instances of single overlap are tracked successfully.

3.3.5.2 Use of Only a Top Antenna

Figure 3-41 shows the tracks formed by the improved processor using replies from whisper-shout interrogations only on the top antenna. with the reply processor operating in the phantom elimination mode. The tracking probability has degraded to 88% and no false targets appear. If the replies include a top, high-power interrogation in addition to the 4 whisper-shouts, the performance as shown in Fig. 3-42 is slightly better than that obtained with whisper-shout on both the top and bottom antennas. It is not unreasonable that additional interrogations improve the surveillance. For example, a transponder may have been in suppression when its whisper-shout interrogation arrived, but can reply to the subsequent high power interrogation.

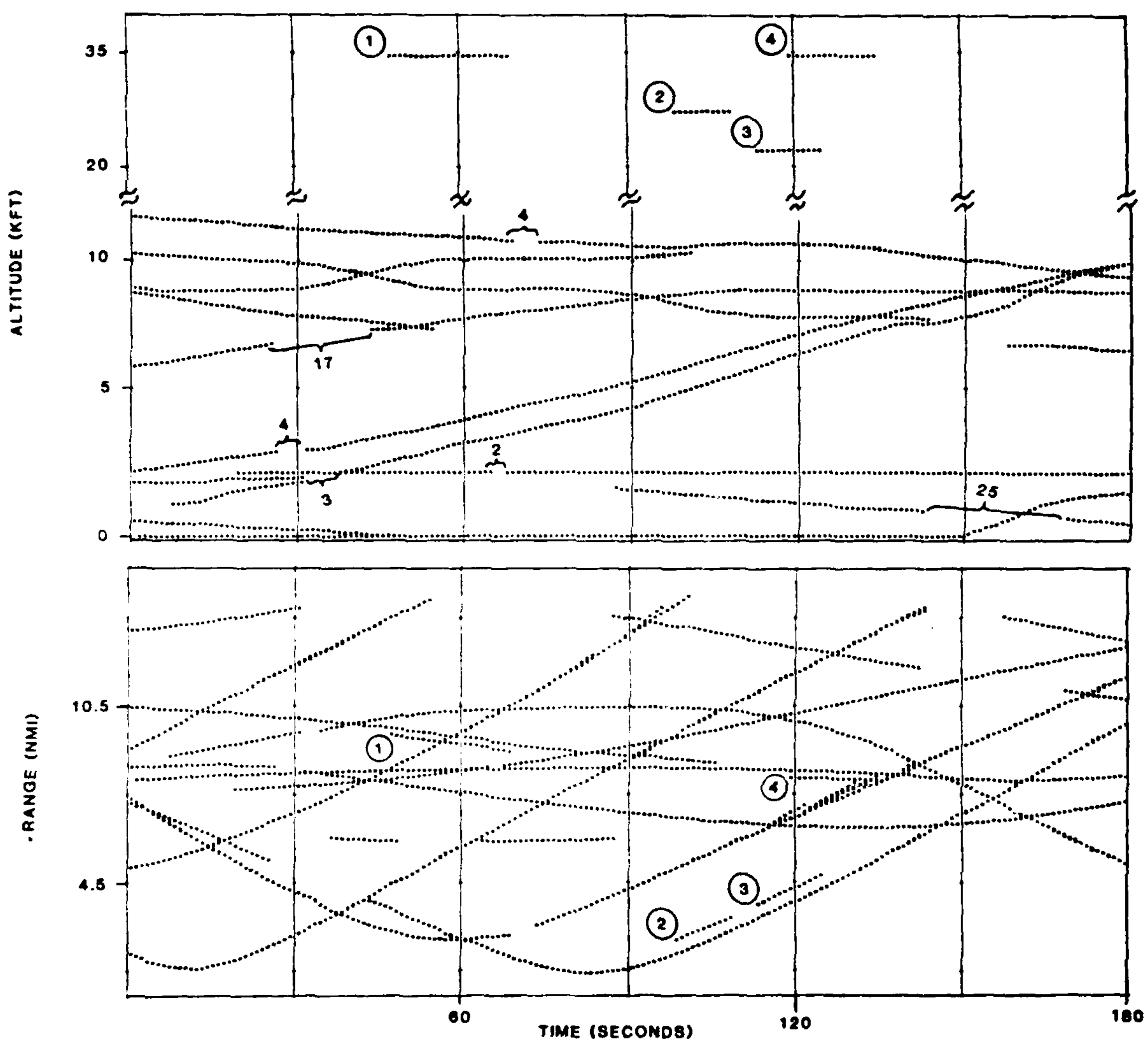


Fig. 3-39. Improved processor tracks (phantoms retained).

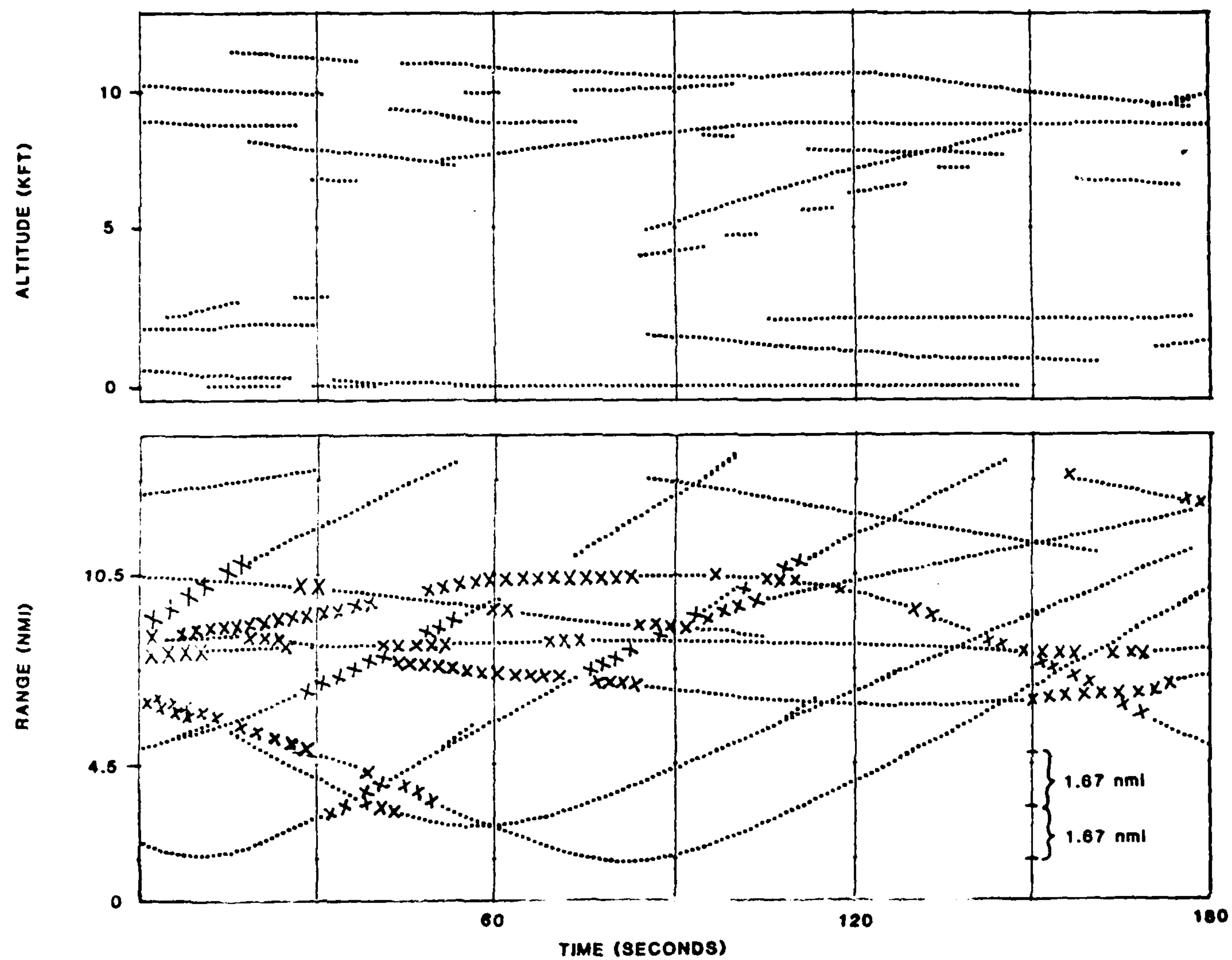


Fig. ? 40. Tracking performance - withour whisper/shout.

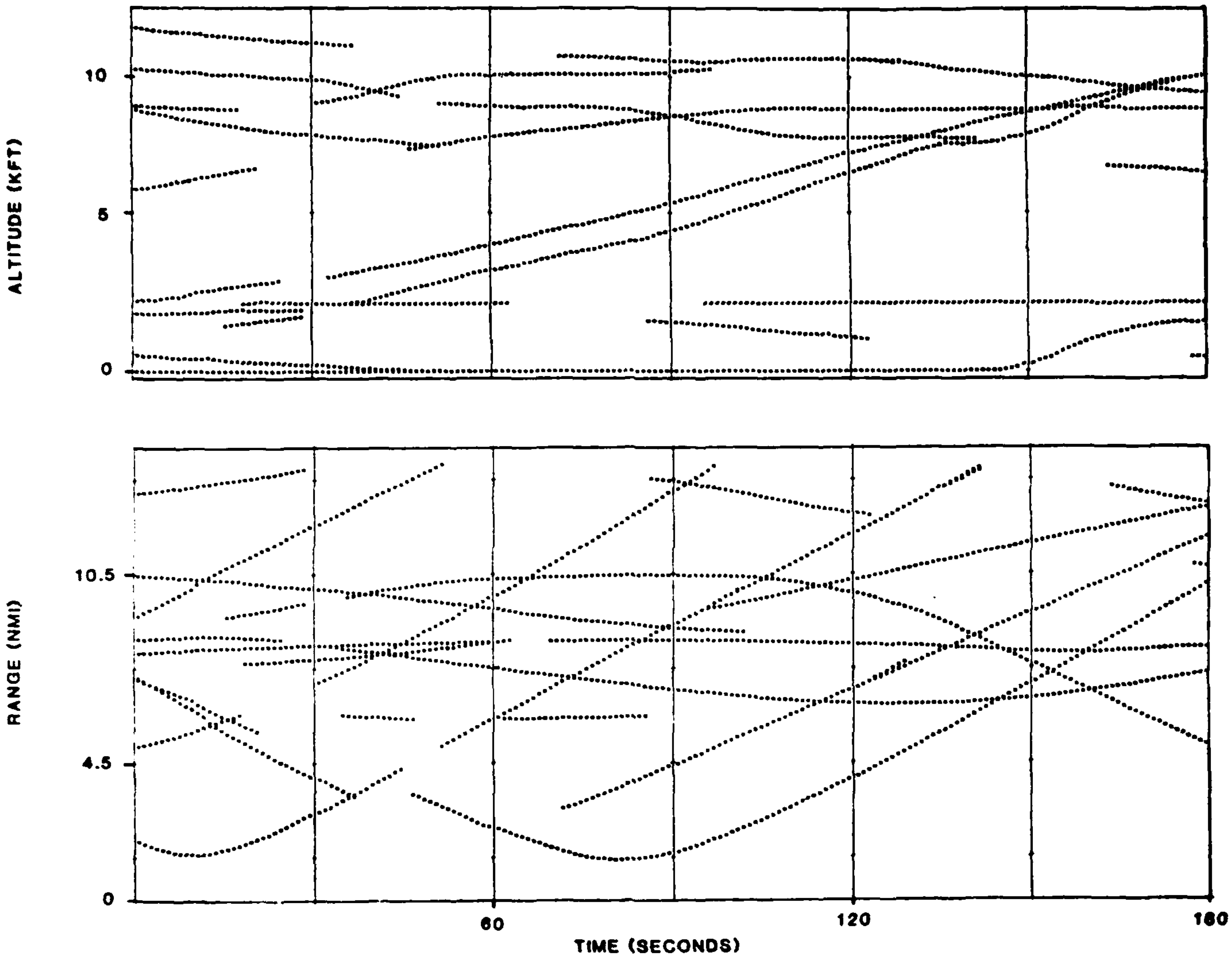


Fig. 3-41. Tracking performance - top antenna whisper/shout.

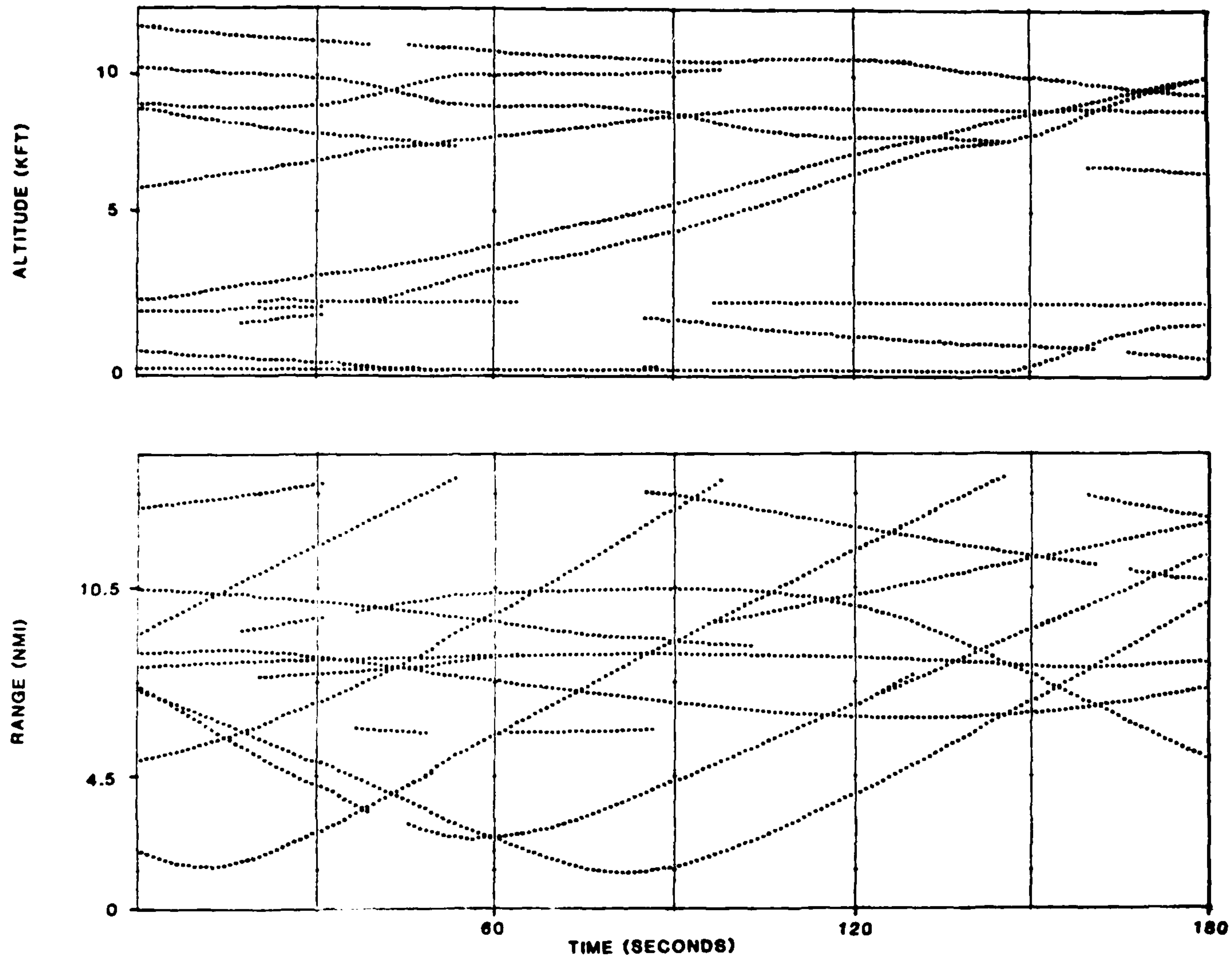


Fig. 3-42. Tracking performance - top antenna whisper/shout plus high power.

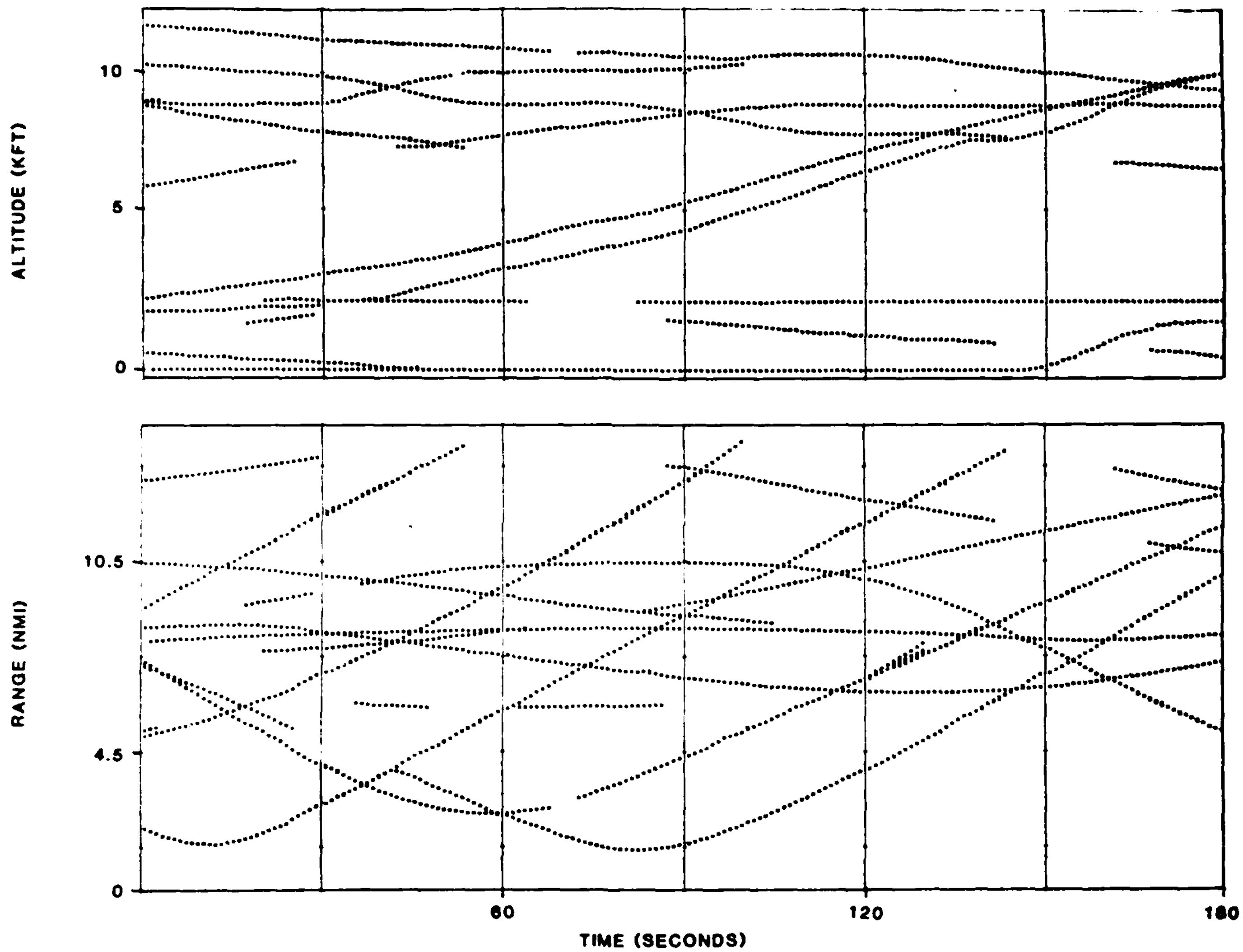


Fig. 3-43. Improved processor tracks 4th whisper/shout on bottom antenna eliminated.

3.3.5.3 Deletion of Some of the Whisper-Shout Levels

Figure 3-43 shows the tracks formed by the improved processor using replies from 4 whisper-shout levels on the top antenna and the 3 low-power whisper-shout levels on the bottom. The tracking probability degraded very slightly to 94%, and there were no false tracks.

3.3.6. Elimination of Ocean Multipath

An algorithm has been developed to delete false tracks caused by ungarbled multipath replies from the ocean surface or terrain surfaces at sea level. These false tracks appear beyond the range of the real track and correspond to reflections on both the up and down links, or reflection on only one of the links.

The algorithm operates as follows. The range rate and altitude of each track is combined with the altitude of the BCAS aircraft to compute two hypothetical range/range rate pairs corresponding to one-way and two-way multipath. Then the distant tracks are compared to these hypothetical ranges and range rates. A correlating track that is within about 1000 feet in altitude of the track used to compute the hypothetical tracks is deleted. Figures 3-44 and 3-45 show the elimination of several multipath tracks.

Note that false tracks can only be deleted if a) a track exists on the real aircraft, and b) the altitude of the false track is near that of the real aircraft, and c) the assumption of a sea-level reflecting surface is valid.

3.3.7. Track Number Continuity

Examination of the maneuver commands generated by the CAS algorithms revealed a number of cases of command instability. Many such cases were found to be caused by the ATCRBS surveillance processing. Typically surveillance processing had the aircraft in track, but the track terminated at the beginning of the encounter and a different track took its place, causing a track number change.

These track number changes were found to be caused by the multiple-extension feature of the original surveillance processing algorithm. In particular, a track was extended for each reply that correlated in range and altitude, opening up the possibility of track splits. If the track merge function then deleted the older track in favor of the just created split, a track number change resulted. These track number changes were virtually eliminated by modifying the processing so that a track can be correlated and extended by only one reply. Among the replies that satisfy the initial correlation test, the reply chosen for extension is the one at shortest range, not used to extend a track at shorter range. Figure 3-44 illustrates the improvement. Different track numbers are shown using different plotting symbols.

The selection of the nearest correlating replies mitigates against extending with multipath replies. The requirement that the correlating reply must not have been used to extend a shorter range track prevents two tracks at the same altitude and crossing in range from using the same reply for extension.

(a) BEFORE

(b) AFTER

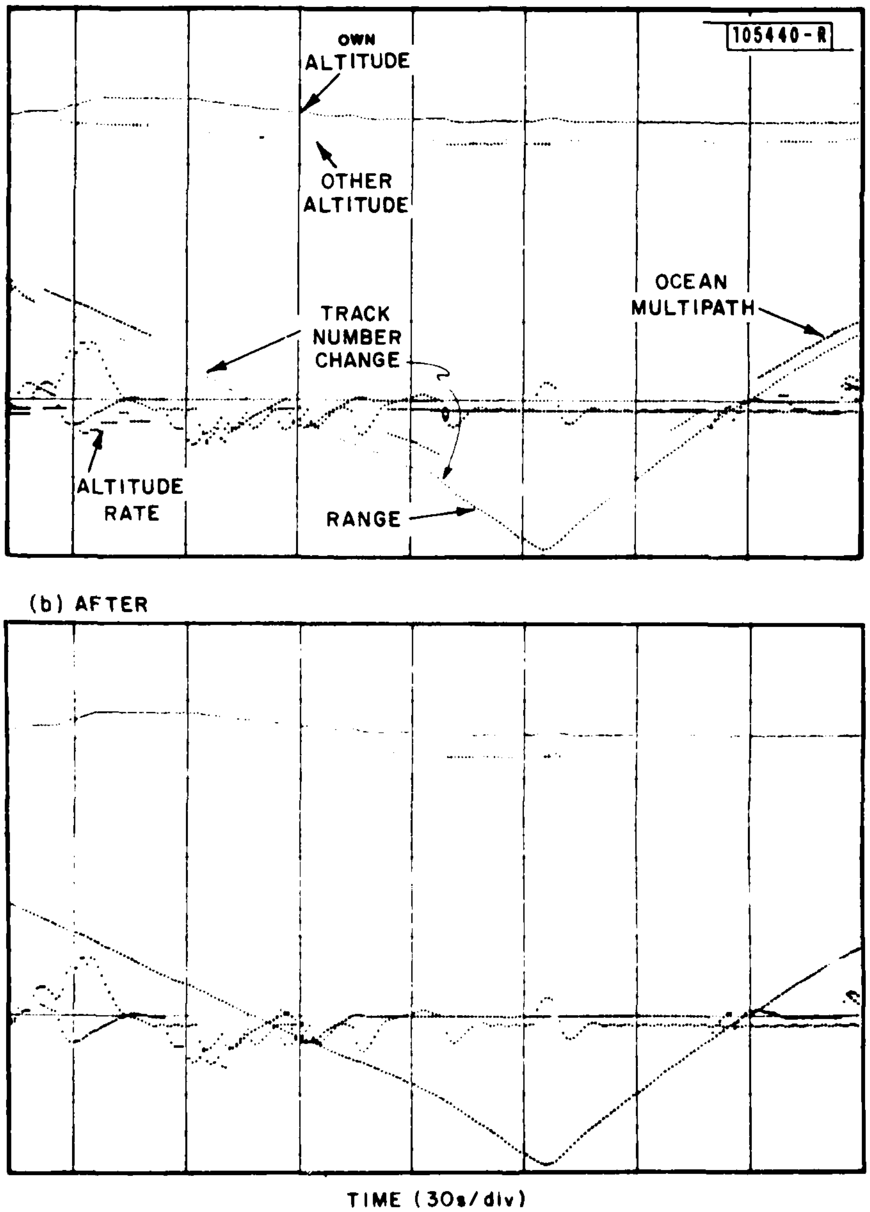


Fig. 3-44. Ocean multipath and track continuity improvements.

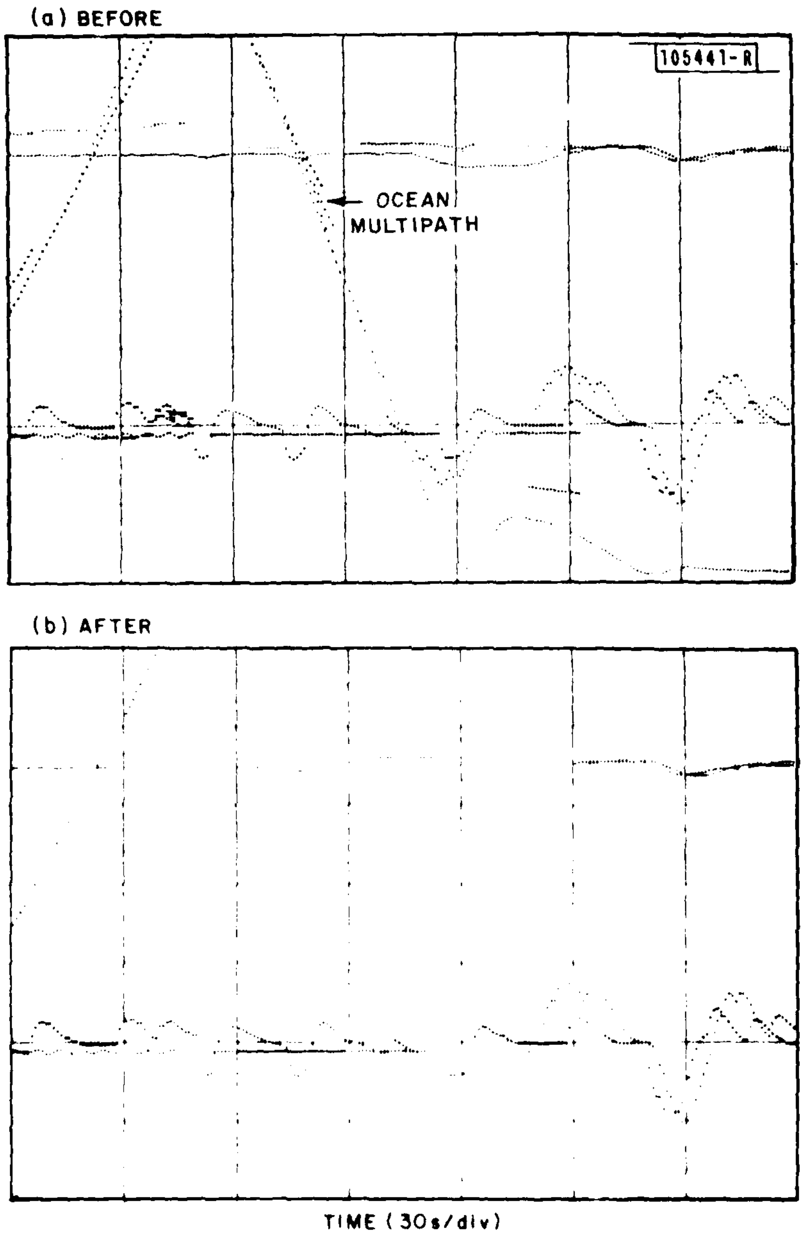


Fig. 3-45. Ocean multipath and track continuity improvements.

3.3.8. Three vs. Four ATCRBS Reply Decoders

Whereas the BFU employs four ATCRBS reply decoders. the FAA requested an assessment of a design employing three. To understand the significance of this difference, a comparative study was conducted of performance achievable both ways.

The study made use of airborne data recorded by the AMF during a 10-minute mission in the Boston area 2 April 1980. The average traffic density during this experiment, over the region within 10 nmi of the AMF, was 0.026 ATCRBS transponders per sq. nmi. Restricting attention to transponders that report altitude, the density within 10 nmi was 0.018 per sq. nmi. These figures refer to the time and spatial average. The traffic exhibited peaking in both time and space, so that at certain times and at certain ranges the surveillance subsystem had to deal with densities much greater than this average.

As noted in Section 2, the AMF accomplishes pulse detection in real-time hardware and records the pulse data. All further BCAS surveillance functions (reply processing and surveillance processing) are implemented in non-real time software. Thus it is possible to process the AMF data with all conditions identical except using 4 reply decoders in one case and 3 decoders in the other.

The results were examined by focusing on "established tracks", which constitute the final output of the BCAS surveillance subsystem. The main observation is that nearly all tracks are identical in the two cases. On close examintion one finds instances in which for a certain aircraft and for a certain brief period of time, the 4-decoder design produces an established track and the 3-decoder design does not. The opposite was also seen to happen, but only once in the 10 minutes of data. All such instances were identified and counted second-by-second. The following statistics summarize the result of the change from 4 decoders to 3 decoders:

Track Losses

Number of instances = 7
Total duration = 41 aircraft-seconds

Track Gains

Number of instances = 1
Total duration = 4 aircraft-seconds

Percentage change

Total sample = 4590 aircraft-seconds
Net loss = 37 aircraft-seconds
Percentage loss = 0.8%

This is a very small change in detection performance. There was also a change in false tracks. In two instances, short-duration false tracks occurred in the 4-decoder design that did not occur in the 3-decoder design.

Both changes in performance are in directions consistent with what would be expected from this design change. It also seems reasonable that the changes in performance are so small, particularly when assessed in traffic densities up to 0.02 aircraft per sq. nmi. One important factor that causes this change in performance to be relatively insignificant is the ability of the system to establish track in just a few seconds after receipt of the first reply. Otherwise it would be necessary to initiate tracks at longer ranges where synchronous garble conditions are worse, and in such a design the 4th decoder would have more of a payoff.

In summary, a change from 4 ATCRBS reply decoders to 3 has two minor effects, a decrease in the probability of tracking real aircraft, and a decrease in the rate of false tracks. In traffic density up to 0.02 aircraft per sq. nmi, both effects are small. The 4-decoder design seems inherently better and probably should be selected in any implementation for which the cost of the fourth decoder is not an issue. On the other hand, a 3-decoder design would be acceptable.

3.3.9. San Diego Encounter Performance

Air-to-air measurements were conducted to determine how well the ATCRBS-mode of Active BCAS would perform in the geometry of the San Diego collision (the September 1978 mid-air collision between a Boeing 727 Air Carrier aircraft and a Cessna 172 General Aviation aircraft). In the experiment the larger aircraft was BCAS-equipped and the smaller aircraft was equipped as in the real incident with an ATCRBS transponder employing a single bottom-mounted antenna.

The performance of BCAS under the conditions of this accident is of particular interest because these conditions stress the air-to-air link. Conditions such as:

- target below the BCAS aircraft
- target equipped with a low bottom antenna
- low altitude

may be expected to accentuate the effects of multipath.

3.3.9.1 Measurement Conditions

In these measurements, a Convair 580 was used to represent the larger aircraft, while a Cessna 172 was used to represent the Cessna 172 of the accident. These tests were a joint effort of the FAA Technical Center and Lincoln Laboratory, the Convair 580 being an FAA aircraft.

In the reconstructed encounter, the two aircraft were flown in the same direction, with the BCAS aircraft descending, and with the transponder equipped aircraft below and climbing. Experiments were conducted for a family of three encounters having slightly different geometries. The horizontal and

vertical speeds in these encounters are given in Table 3-5. Each pilot kept the other aircraft in sight, and as they came together deviated slightly from course to effect a safe passage. After passing they continued on for about another minute.

The AMF was installed in the Convair 580. The BCAS functions were carried out (in non-real-time) by using the measurements of the AMF combined with postmission processing of the AMF data.

TABLE 3-5.

EXPERIMENTAL CONDITIONS -- SAN DIEGO TESTS

Experiment Number	Speed (knots)		Altitude Rate (ft./min.)	
	BCAS	Target	BCAS	Target
848 A	150	75	-500	500
848 B	150	75	-500	800
848 C	150	75	-1000	800

3.3.9.2 Results

The results of these measurements indicate successful BCAS surveillance performance. The ATCRBS reply detections from experiment 848C (which is typical of the three experiments) are plotted in Fig. 3-46. These results indicate that replies were reliably received, giving the range and altitude of this target over the full duration of the experiment, which begins about 70 seconds prior to the time of closest approach. The tracked outputs from this experiment are plotted in Fig. 3-47. As would be expected from the quality of the reply data, a track was established promptly, and it was maintained continuously and correctly in both range and altitude for the full duration of the encounter.

This experiment was later repeated several times using a Boeing 727 and Cessna 172 with essentially identical results.

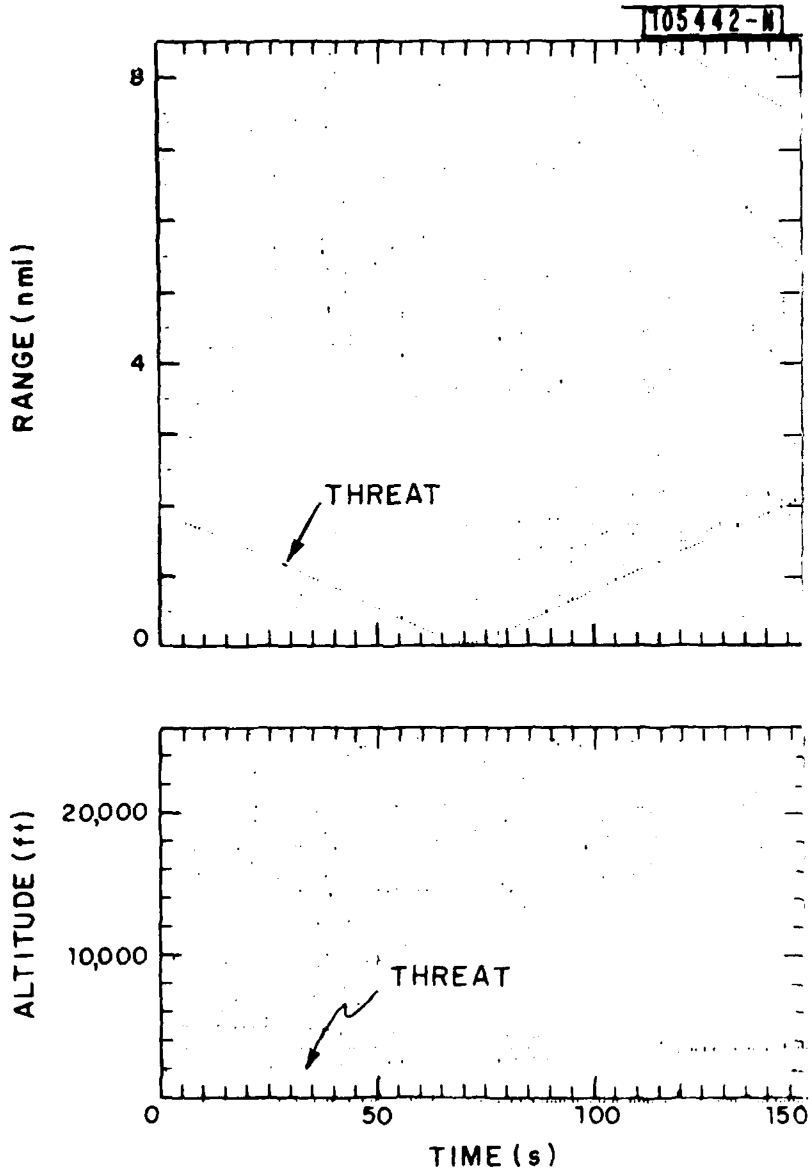


Fig. 3-46. BCAS reply performance - San Diego collision geometry.

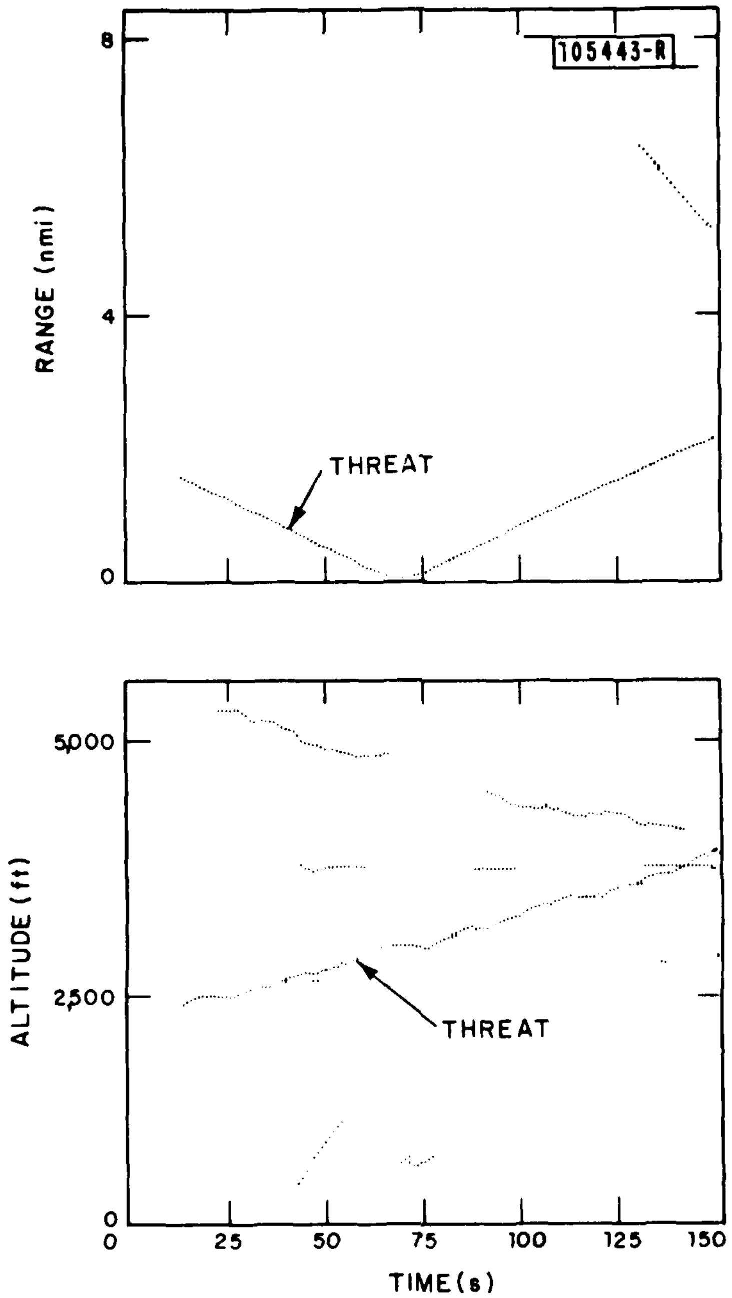


Fig. 3-47. BCAS performance - San Diego collision geometry.

4. ASSESSMENT OF ATCRBS MODE SURVEILLANCE IN AN OPERATIONAL ENVIRONMENT

A series of flights conducted in September 1980 provides a useful data base for an assessment of the ATCRBS-mode performance of the BCAS design that has evolved. These were flights of the Boeing 727 aircraft operated by the FAA (tail number N40). The missions were flown along the East Coast of the U.S. including both enroute and terminal phases of flight on typical air carrier flight paths. Also included were a number of landings and take-offs at New York, Washington D.C., and Atlanta. The aircraft. N40, was equipped with a BEU, which (as described in Sec. 2) carries out all of the BCAS functions in real time including the generation of a pilot display. During these flights. two displays were operative: an IVSI for display of maneuver advisories, and a traffic situation display implemented with a Lincoln Laboratory AID (Airborne Intelligent Display)*. A peripheral tape recorder attached to the BEU provided a detailed recording of all events during the mission for later analysis. It is these tape recordings. processed in the manner illustrated in Fig. 2-4, that provide the basis for the BCAS assessment reported here.

4.1 The Data Base

A total of about 560 minutes of data was analyzed from the New York City, Atlanta, and Washington/Baltimore areas, including enroute flight between these cities.

The portion recorded enroute from Atlantic City to Atlanta (70 minutes), and in the Atlanta terminal area (109 minutes) totals about 179 minutes. During the 10740 scans (one sec. each), there was a total of 54374 track-seconds. Thus the average number of aircraft in track in one scan was about 5 (within 14 nmi). While in the terminal area, the number of tracks was considerably greater, and the peak number was about 18. These figures give some indication of the aircraft density through which the Boeing 727 flew. More detailed information regarding density and its effects on BCAS performance is given below in Section 4.4.4.

A total of 160 minutes of data was recorded in the Washington Baltimore area. During the 9600 scans, there were 63212 track-seconds. or an average of about 7 aircraft in track at one time.

A total of 221 minutes of data was recorded in the JFK, Newark, and La Guardia area. During the 13260 scans, there were 107035 track-seconds, or an average of about 8 aircraft in track at one time.

*A modified weather radar color CRT driven by a Z80 microcomputer system to display traffic range, range rate and altitude.

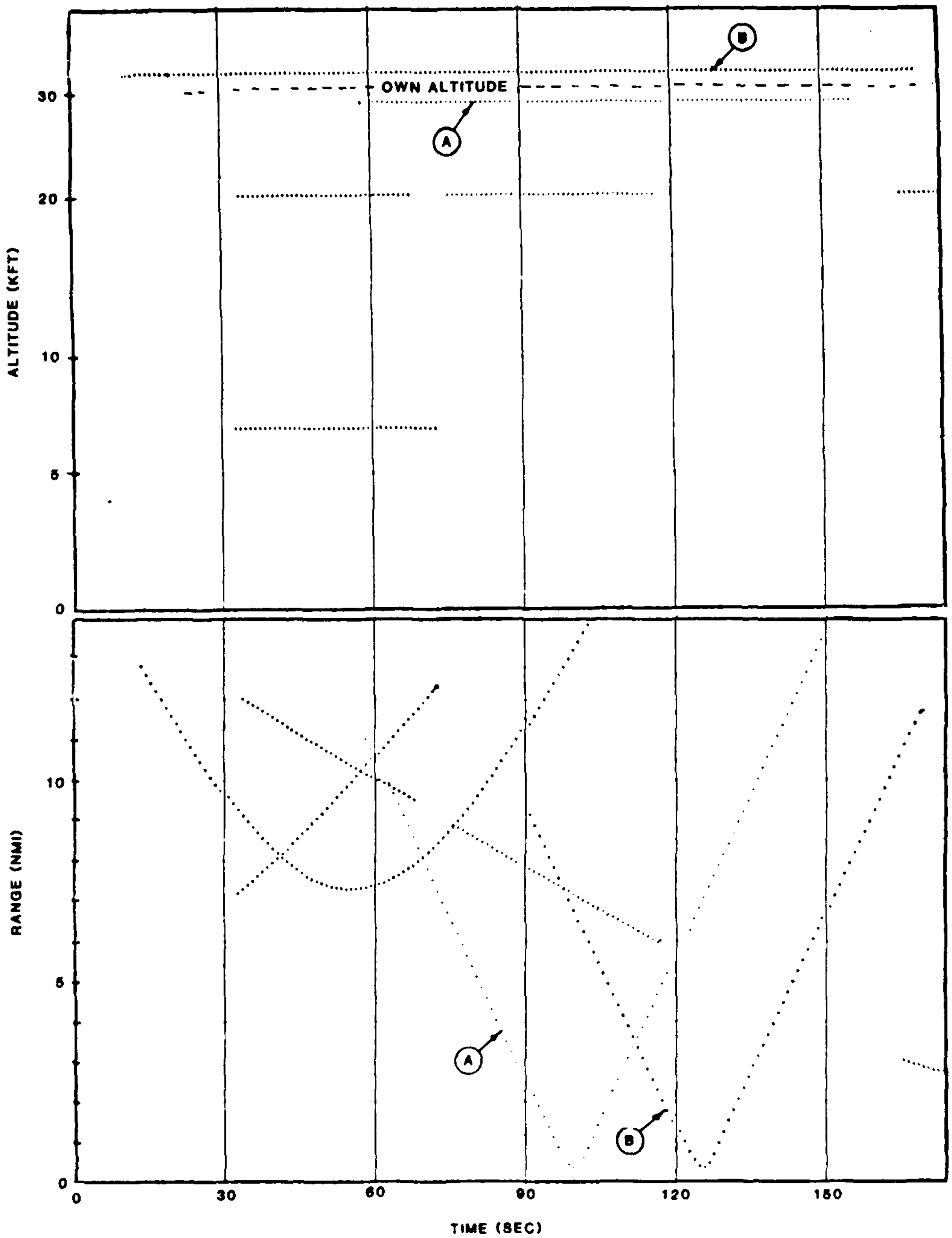


Fig. 4-1. Chance encounters at high closing rate.

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4.2 Detection at Long Range

Whereas most BCAS tracks of interest will occur at ranges less than 4 nmi, the capability to detect aircraft at longer range is built into BCAS equipment to give protection for the possibility of very high speed encounters. The September 1980 data base includes a number of chance encounters at high closing speeds, which afford an opportunity to assess performance at long range. For example, the range and altitude tracks from two high speed encounters are shown in Fig. 4-1. This is a plot of "established tracks", which are tracks of high confidence used as the input to BCAS threat logic. The encounter marked A can be seen to have a closing rate of 990 knots and a PCA (point of closest approach) of 0.3 nmi, with the other aircraft passing below N40 by about 1000 feet. The two aircraft were probably passing in opposite or nearly opposite directions. The BCAS track was established at a range of 11.2 nmi, which occurred 43 seconds before PCA. Thereafter the track was continued, without any drops, through PCA and beyond. During the 43 seconds prior to PCA, there was a single coast (not shown in the figure). so that the blip/scan ratio was about 98%.

The situation in encounter B is similar: closing speed = 960 knots, PCA = 0.3 nmi, track establishment range = 9.3 nmi, time = 36 sec before PCA, track continuity = 100%, number of coasts = 2, blip/scan ratio = 94%.

Throughout the September 1980 data base there are a number of other chance encounters at high closing speeds (although, because of differences in altitude, none of these encounters resulted in a maneuver advisory). Their characteristics along with the resulting BCAS performance are listed in Table 4-1. Traffic densities of aircraft reporting altitude are also listed in the table. Here, density was calculated by counting the aircraft (other than the subject aircraft) within 10 nmi, averaging this count over a one minute period centered at PCA, and then dividing this result by π times 10 nmi squared. It is evident that most of these encounters occurred in low traffic density, and all resulted in excellent performance. In Case G, in the Washington area, the traffic density was medium high (0.015 altitude reporting aircraft per nmi^2), while the closing rate was fairly high, and still the performance was excellent.

Thus with respect to detection at long range, the performance throughout the September 1980 data base was nearly perfect: in all cases of high speed encounters, track was established early enough for 36 seconds or more of warning time, and the track was continued without a drop through PCA.

4.3 Performance in Higher Traffic Densities

The next area of investigation is performance in higher traffic densities. It is to be expected that the presence of numerous other aircraft will lead to more and more synchronous garble, more and more coasts, and eventually to occasional drops of track. In selecting cases of particular interest, a useful starting point is the identification of all cases in which some maneuver advisory was generated (not counting the brief periods just before landing or during takeoff). Interestingly there were none: no positive or negative or limit-rate advisories were generated during the several hours of flight.

TABLE 4-1.

BEU PERFORMANCE IN CHANCE HIGH-SPEED ENCOUNTERS

	Case	BCAS Alt. (ft)	Other Alt. (ft)	Density* aircraft sq nmi	Closing Speed (kt)	PCA (nmi)	Acquisition Range (nmi)	Acq. Time (sec. before PCA)	Track Continuity Inbound (%)	Coasts Inbound
A	Enroute-NJ to Atlanta	30,300	28,800	0.006	990	0.3	11.2	43	100	1/43=2%
B	Enroute-NJ to Atlanta	30,300	32,700	0.004	960	0.3	9.3	36	100	2/36=6%
C	Enroute-Atlanta to Miami	26,300	32,700	0	930	2.3	>13.0	>49	100	0
D	Enroute-Atlanta to Miami	26,300	32,900	0.003	960	4.0	13.0	47	100	2/47=4%
E	Enroute-Atlanta to Miami	26,300	28,800	0.003	1020	2.0	11.2	40	100	2/40=5%
F	Enroute-Atlanta to Miami	26,300	32,600	0.002	840	3.5	12.8	49	100	0
G	Wash'ton	12,000	11,000	0.015	540	1.6	>9.5	>64	100	3/64=5%

*This is the density of only the altitude reporting aircraft.

Since no aircraft penetrated the threat volume, a reasonable next step is to adopt a somewhat larger volume for use in identifying interesting cases, such as: select an aircraft for examination if it at some time came within 3 nmi in range while being within ±10 degrees in elevation angle. Within the September 1980 data base, there are a number of cases that satisfy this condition, some occurring within higher traffic density. Two are shown in Fig. 4-2, marked as H and I. This sample occurred in the New York area. in a density of 0.024 altitude-reporting aircraft per nmi^2. Each track exists for 100% of the time and each experiences occasional coasts; the update rates are 90% and 81% for tracks H and I respectively.

4.4 Statistical Performance Assessment

In addition to individual case studies such as those described above, statistical performance assessments have been undertaken based on the full data base, and also for the three separate portions identified above as: (1) Atlanta, (2) Washington/Baltimore, and (3) New York. Also, to study the relationship between performance and aircraft density, the data is further subdivided, as described in Section 4.4.4, into numerous small pieces.

4.4.1 Performance Definitions

The performance measures in use may be defined as follows.

Probability of track: For a given scan and a particular aircraft of interest, the probability that an established track of that aircraft exists on that scan.

Probability of report: For a given scan and a particular track of interest. the probability that the track is updated with a report on that scan.

Probability of coast: One minus the probability of report.

4.4.2 Probability of Report

Probability of report and probability of track may be expected to degrade with increasing range, with aircraft turns that result in unfavorable antenna gain, and with increasing number of aircraft within garbling range of each other. When the aircraft distribution is uniform in area (which is true most of the time, at least for ranges to 10 nmi), overlaps increase with increasing range.

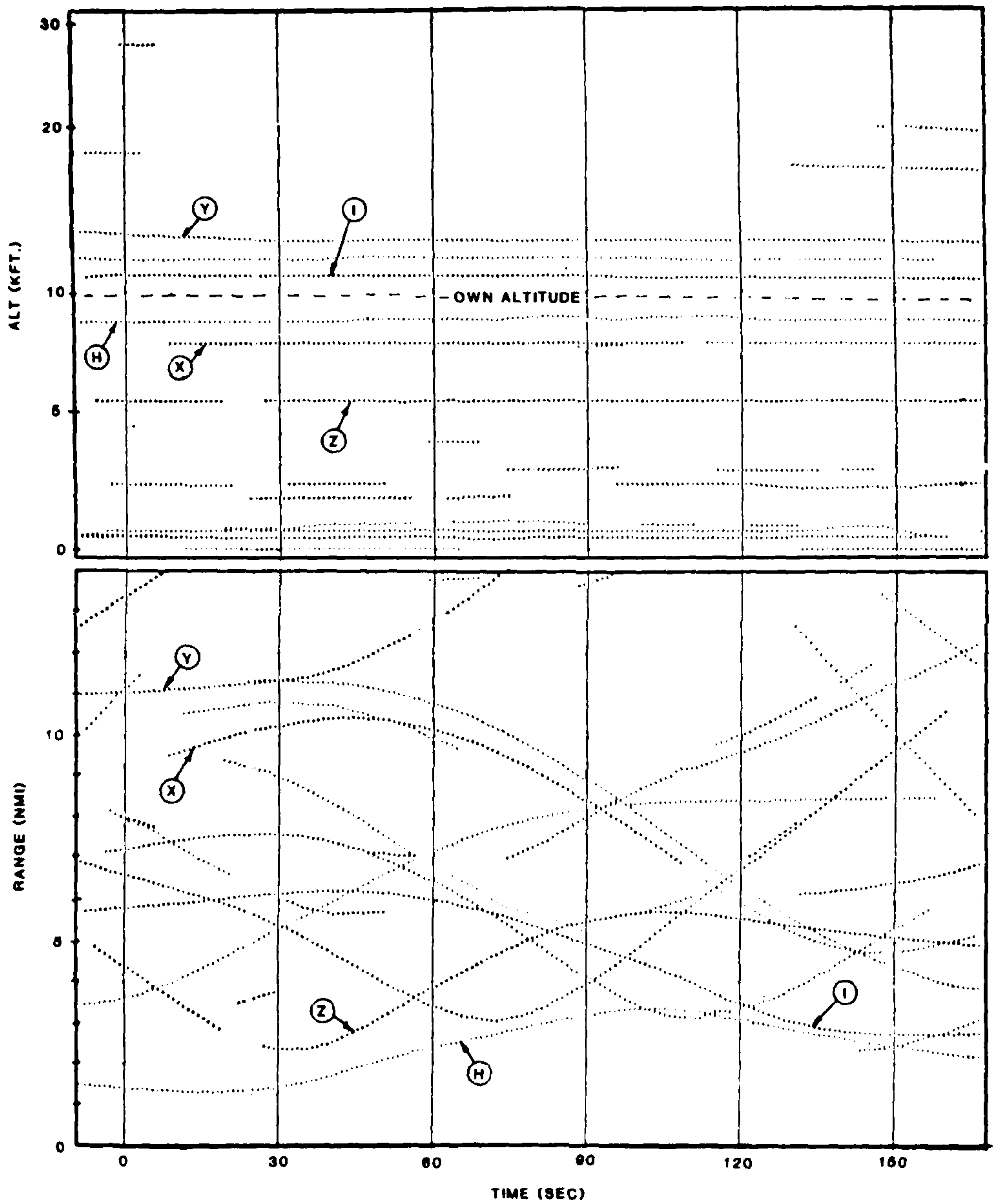

Fig. 4-2. Two tracks of interest in high traffic density (New York).

Probability of report was evaluated from the BEU database by computing the ratio of reports to the sum of reports and coasts. The ratio was evaluated as a function of two variables, range and number of overlaps. Range is divided into three intervals. 0-3 nmi, 3-6 nmi, and 6-9 nmi. The number of overlaps is defined as the number of aircraft within 1.76 nmi in range relative to the subject aircraft. Aircraft further apart in range cannot produce replies that overlap in time. It was not practical to evaluate the update rate as a function of the true number of overlapping aircraft. Instead, number of overlaps was a count of tracked aircraft. This count does not include aircraft that lack altitude reporting. but otherwise is a good estimate of the airborne environment.

Rather than evaluating probability of report over the entire trajectory of every real aircraft, we conducted this evaluation for aircraft "of interest", defined as follows. The time an aircraft spent within 600 ft of ground level was not counted, nor was the time it spent outside ± 10° in elevation angle*. Finally, data was excluded during the time the Boeing 727 was within 600 ft of ground level. Performance when either aircraft was near the ground is excluded from this study simply to focus attention on the primary region in which BCAS is intended to operate. It is also possible to operate BCAS near the ground, and an assessment of performance under such conditions will be the subject of a later study.

The results are shown in Table 4-2. As expected. probability of report degrades with increasing number of overlaps and range, and with increasing range. Given a particular number of overlaps and range, the probability of report is also reasonably independent of geographical location.

4.4.3 Probability of Track

The most important performance measure is probability of track. To evaluate probability of track it would be desirable to have an independent source of surveillance to determine the presence of aircraft. Since an independent source was not available, the only course of action was to apply a superior tracker to the same reply data. This was done manually, using plots of the reply ranges and altitudes versus time. By concentrating primarily on the range plots, the existence of aircraft can be confidently inferred even when round reliabilities were as low as about 25%. Gaps as long as tens of seconds having even lower round reliabilities can confidently be filled in on the basis of only a few replies.

This manual procedure works well except for the region beyond about 9 nmi in high density airspace. Here, the density-in-range of aircraft is so high that it becomes very difficult to reliably determine the trajectories of all aircraft.

*Among the actual mid-air collisions whose geometries are shown in Fig. 3-17, none involved elevation angles beyond ± 9 degrees.

TABLE 4-2.

PROBABILITY OF REPORT EVALUATED FOR AIRCRAFT OF INTEREST

No. of Overlaps	ALT	WASH	NYC	ATL	WASH	NYC	ALT	WASH	NYC
	0 to 3 nmi			3 to 6 nmi			6 to 9 nmi		
0	.92	.96	.92	.91	.92	.86	.88	.87	.86
1	.89	.93	.87	.85	.86	.82	.83	.80	.72
2	.79	.76	.80	.81	.78	.77	.75	.73	.68
3	.80	.83	.78	.78	.76	.74	.67	.69	.63
4	N/A	N/A	N/A	.68	.69	.69	.60	.67	.61

N/A denotes "not available", and refers to the fact that there were no occurrences of 4 overlaps within 3 nmi.

As in the preceding section, this analysis was limited to aircraft in the region of interest. The results of comparing the real aircraft trajectories to the BCAS tracks are shown in Table 4-3. Performance is seen to be excellent, above 95%, throughout the most important region within 3 nmi. As expected, probability of track is best at short ranges while degrading gradually at longer ranges. However even for the interval from 6 to 9 nmi. performance is quite good (about 88%).

4.4.4. Performance as a Function of Aircraft Density

An indication of the aircraft densities during these flights is given in Fig. 4-3, a histogram of the number of targets in track. These figures refer to the number of aircraft within 10 nmi, and include altitude reporting aircraft only. The long enroute flight from Atlantic City to Atlanta is evident as the large fraction of time spent with 0, 1 or 2 targets in track. The equivalent densities marked in the figure are based on the formula:

$$\text{density} = \frac{\text{number of aircraft}}{\pi \times (10\ \text{mmi}^2)}$$

The effect of aircraft density on probability of track for aircraft of interest was evaluated as follows. Range was divided into three intervals: 0-3 nmi. 3-6 nmi, and 6-9 nmi. Tracks were examined in one-minute time segments, and the average number of aircraft within 10 nmi (including aircraft replying without altitude reports) was determined for each segment. Probability of track was estimated using the same technique as described in Sec. 4.4.3, except here the manual task was even more tedious since each one minute period was treated separately. Of the 560 minutes of data, 269 one-minute segments were randomly selected for analysis. The results are shown in Table 4-4. The last column gives the track probability evaluated over all 269 one-minute segments, and agrees very well with the values in Table 4-3 for all 560 minutes.

The performance vs. density data from Table 4-4 is plotted in Figure 4-4, where density was computed as:

$$\frac{\text{average number of aircraft} - 1}{\pi \times (10\ \text{nmi})^2}$$

Performance is seen to be excellent: above 95% throughout the most important region within 3 nmi, and degrading only gradually beyond. The region of short ranges is the most important in the sense that the great majority of BCAS encounters will occur with much less than the design maximum closing speed, and so the ranges at which tracking is required will in most cases be much less than the maximum. Cases requiring tracking at longer range will be a minority, and especially rare will be the cases in which both long range and high density performance are needed simultaneously.

TABLE 4-3

PROBABILITY OF TRACK EVALUATED FOR AIRCRAFT OF INTEREST

Data Set	Range Intervals (nmi)		
	0-3	3-6	6-9
Atlanta	.97	.96	.90
Washington/ Baltimore	.98	.94	.90
New York	.97	.90	.86
Full Data Base	.97	.92	.88

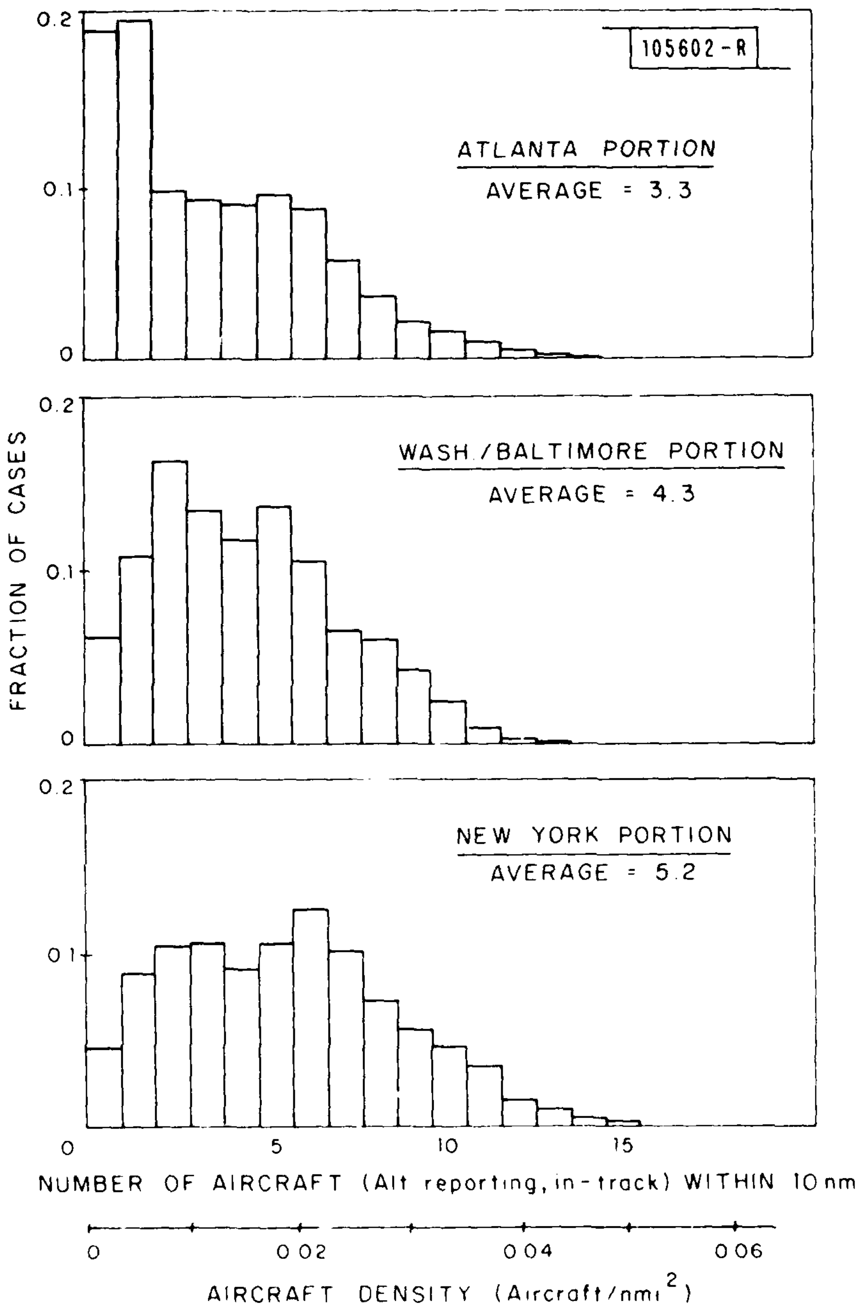

Fig. 4-3. Aircraft counts and densities.

TABLE 4-4

PROBABILITY OF TRACK VS DENSITY EVALUATED FOR AIRCRAFT OF INTEREST

range (nmi)		Number of ATCRBS transponders within 10 nmi								
		1or2	3or4	5or6	7or8	9or10	11or12	13or14	15or16	1 through 16
	6-9	250	265	318	528	708	519	535	311	3434
		2244	3261	2445	5271	4005	1601	1291	720	20838
		.90	.92	.88	.91	.85	.76	.71	.70	.86
	3-6	18	63	144	194	256	200	143	182	1200
		670	1562	2050	3139	2768	1650	851	739	13429
		.98	.96	.93	.94	.92	.89	.86	.80	.92
	0-3	0	0	7	31	1	0	0	0	39
		364	139	364	332	530	395	133	109	2366
		1.00	1.00	.98	.91	1.00	1.00	1.00	1.00	.98

Note: The three entries in each case are

(a) number of aircraft-seconds for which there was no track

(b) number of aircraft-seconds for which there was a track

(c) probability of track = $\frac{(b)}{(a)+(b)}$

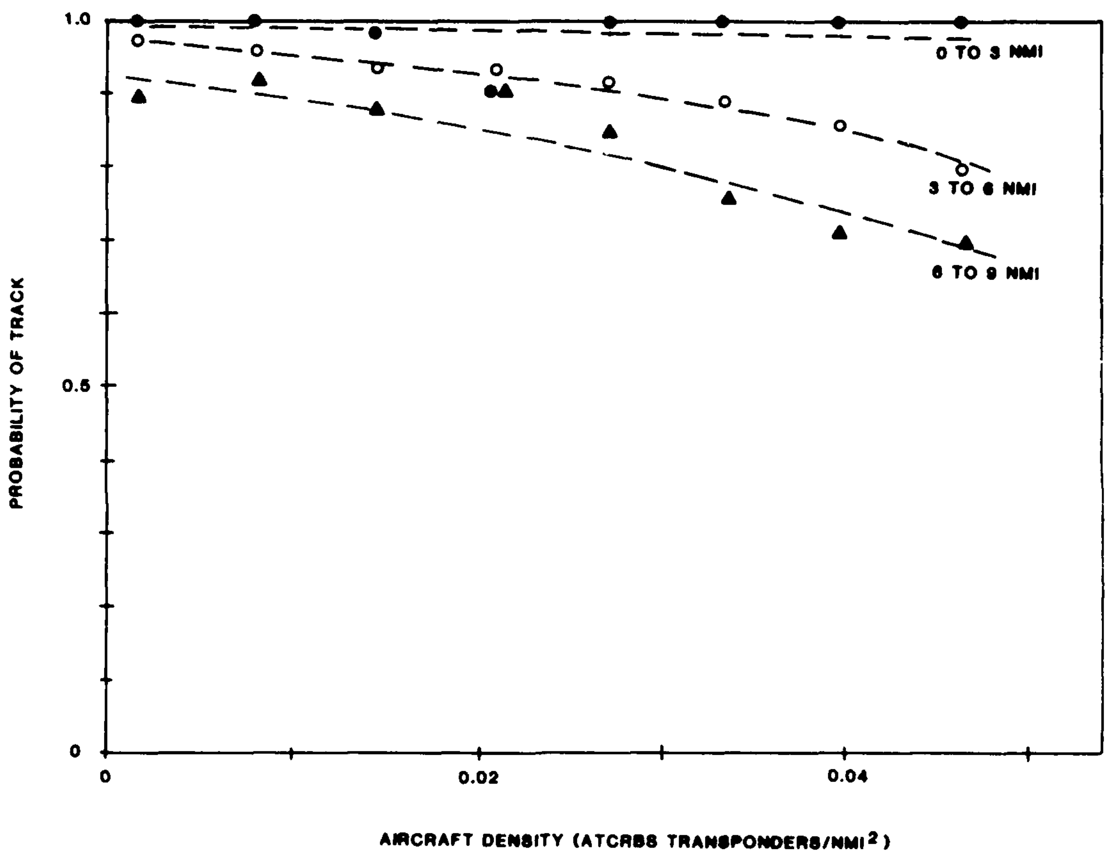

Fig. 4-4. Tracking performance vs density and range.

These considerations can be put into a quantitative form as follows. Let $P(T|R,D)$ denote the data in Table 4-4, which is the conditional probability of successful tracking (T), given range (R), and traffic density (D). From this, the unconditional probability of tracking, denoted $P(T)$, can be determined from:

$$P(T) = \iint P(T|R,D)\, P(R,D)\, dRdD$$

where $P(R,D)$ is the frequency of occurrence of various range-density combinations. Range R represents the maximum range at which a particular aircraft must be tracked in order to provide timely pilot warning. Thus R is related to closing speed S by the threat boundary equation:

$$R = DMOD + (tau \times S)$$

where tau and DMOD are the slope and offset threat parameters.

$P(R,D)$ can be estimated from BEU data, as for example in the scattergram shown in Fig. 4-5. This was generated by the procedure: select from all of the aircraft tracks those that at some time were within 3 nmi in range while converging and while being within $\pm$ 10° in elevation angle. In the Atlanta portion of the data base (which is 179 minutes in duration) there are a total of 18 aircraft tracks that qualify, and these are the 18 points in Fig. 4-5. In each case, closing rate was determined by using the maximum of the rate averaged over 30 second periods, and the aircraft density was determined by averaging over 1 minute the number of aircraft within 10 nmi range, not counting the target aircraft, and dividing this number by π times 10 nmi squared (including all aircraft replying to mode C, with or without altitude data). In each case, it was noted whether the BEU equipped aircraft was above or below 10,000 ft. in altitude, since the threat boundary parameters change at that point.

The scattergram confirms the general expectation: high closing speeds do occur, but are far less numerous than lower closing speeds, and are usually in low traffic density.

In making use of this scattergram as an estimate of $P(R,D)$ the calculation of unconditional tracking probability becomes simply:

$$P(T) = \sum_{i=1}^{18} P(T|R_i, D_i) \times \frac{1}{18}$$

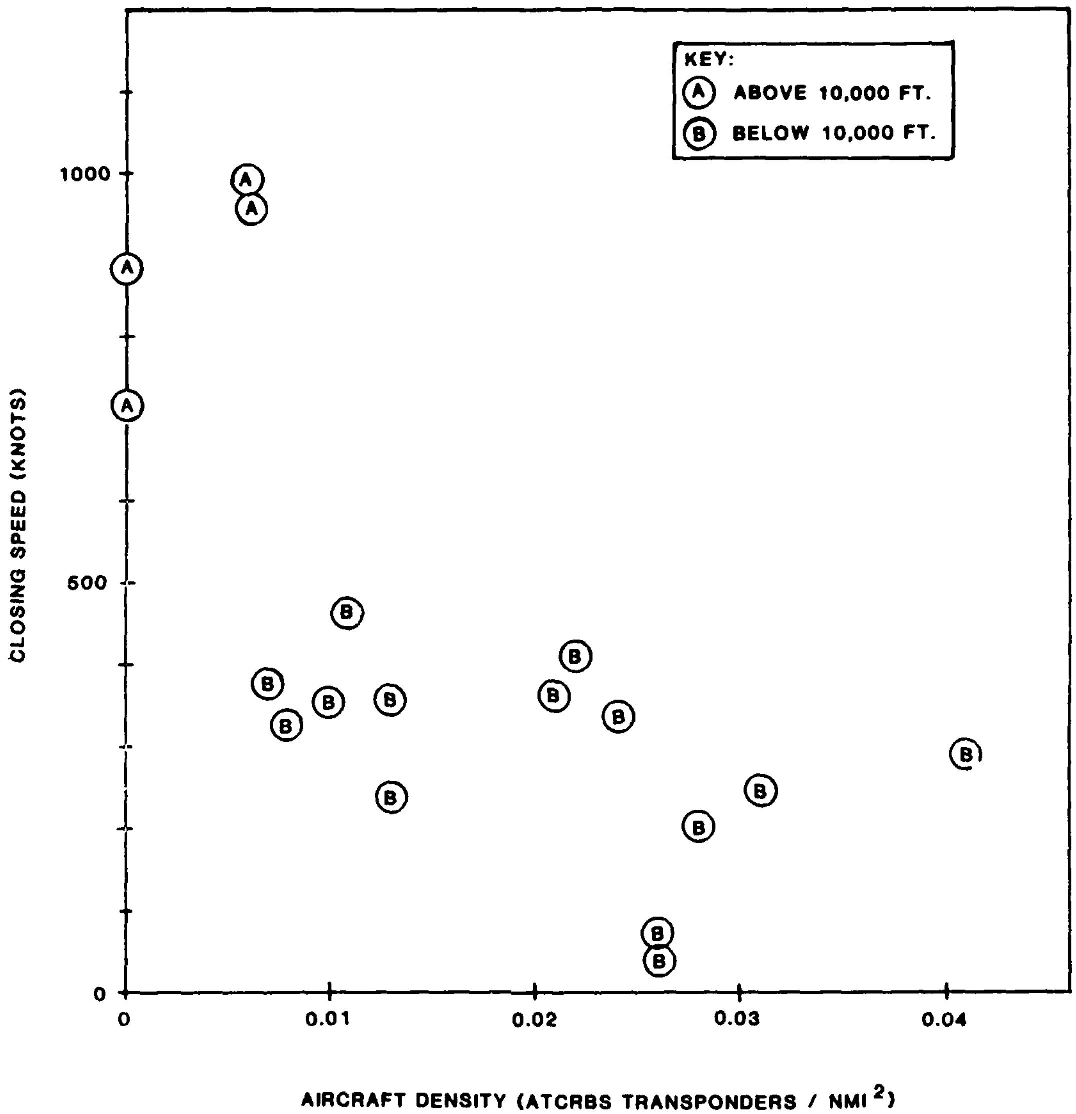

Fig. 4-5. Frequency of occurrence of speed - density combinations.

where the pairs (R_i, D_i) are the 18 range and density points in the scattergram. This calculation has been carried out, using tau = 30 sec. and DMOD = 1 nmi above 10,000 feet, and using tau = 25 sec. and DMOD = 0.3 nmi otherwise. For example, in one case occurring below 10,000 ft., the closing speed is 246 knots and the density is 0.013 aircraft per sq. nmi. At this speed the threat boundary is penetrated at 2.0 nmi. In this density, the average number of aircraft within 10 nmi, including the subject aircraft, is 5. Thus from Table 4-4, we obtain $P(T|R_i, D_i) = 0.95$ for this one contribution. The final result is

$$P(T) = 0.96$$

This is a rough estimate of the unconditional probability of successful tracking, or in other words, the overall average tracking success ratio for a full population of encounters with a realistic mix of closing speeds and traffic densities. This figure includes the possibility of flying into high density areas and the possibility of encountering other aircraft at high closing speeds, with these events combined into this overall average in proportion to their frequencies of occurrence.

4.4.5. False Tracks

Since, as mentioned above, there were no maneuver advisories at any time in the data base from several hours of flight, of course there were no incidences of false alarms. It is useful however to identify and count false tracks since these may serve as an indication of the false alarm rate.

The false tracks that occurred in the 0-9 nmi, ±10°, 600-feet-above ground level region were counted with the following results:

Atlanta: 4
Washington/Baltimore: 4
NYC Area: 6

The longest false track lasted 11 seconds, and the average duration was 7 seconds. The majority occurred at a range of about 6 nmi. Thus the rate of false tracks in the region of interest over the 560 minutes of data was 1.5 false tracks per hour*.

The rate of false alarms (false maneuver advisories displayed to the pilot) may be expected to be much lower, since only a small fraction of false tracks satisfy the alarm criteria. An accurate estimate of false alarm rate would be difficult to obtain from this data, because in fact no false alarms actually occurred, and therefore an extrapolation would be needed. Perhaps the most useful piece of relevant information is the fact that in the more extensive BEU airborne testing by the FAA, no false alarms have occurred in several hundred flight hours.

*The false track rate of 5 per hour reported above in Sec. 3.2.4.3.1 includes all false tracks regardless of location. This is not inconsistent with the value given here, 1.5 per hour, since the latter is limited to tracks in the region of interest.

5. SUMMARY AND CONCLUSIONS

The development of BCAS equipment has been based on a broad foundation of data from airborne measurements together with analyses, detailed simulations, and finally experimentation with real-time BCAS models. The most important conclusion is that it is possible to build BCAS equipment that will reliably carry out the surveillance task intended. Reliable air-to-air surveillance has been achieved in both the DABS and ATCRBS modes.

Many design issues have been addressed, and these studies have resulted in a number of specific conclusions, summarized in the following sections.

5.1 The BCAS Link

If the BCAS airborne equipment uses a transmit power and a receiver sensitivity which are equivalent to that of a DABS transponder, and if the BCAS unit employs both top and bottom-mounted antenas, the air-to-air link has sufficient margin to adequately detect aircraft closing at speeds up to 1200 kt, and the link reliability improves rapidly as the closing speed is reduced.

5.2 Diversity

5.2.1 Diversity in the BCAS Equipment

It is essential that all airborne BCAS units employ top-mounted antennas. The top antenna provides a significant level of immunity to the effects of ground-bounce multipath particularly when the target aircraft is a normal ATCRBS installation with only a bottom-mounted transponder antenna. It is recommended that every BCAS airborne unit also employ a bottom-mounted antenna to provide coverage for targets below the BCAS aircraft. However, the data supporting this latter recommendation are not compelling; an airborne BCAS installation using only a top-mounted antenna should not be ruled out at this time.

5.2.2 DABS Transponder Diversity

One of the most important issues examined in this program was whether the DABS transponder must have dual diversity antennas to support reliable air-to-air surveillance by BCAS. It was found that BCAS achieves near-perfect performance when the target is equipped with a DABS diversity transponder. It was found that BCAS (which itself employs top and bottom antennas) provides somewhat degraded surveillance performance against non-diversity DABS transponders.

5.3 DABS Surveillance

5.3.1 DABS Interrogation Link

It is essential that the local transponder on board the BCAS aircraft be suppressed each time the BCAS unit transmits to prevent the echoes of the interrogation from triggering the transponder, thereby interfering with the desired reply.

The DABS air-to-air interrogation link performs reliably without need of further special precautions or modifications. The DABS interrogation data block is protected from multipath by the inherent interference resistance of the binary phase modulation process, and the DABS pulse preamble is protected by the standard transponder echo suppression circuitry.

5.3.2 DABS Reply Link

Like the DABS interrogation data block, the DABS reply data block is also naturally resistant to multipath since the pulse position demodulation process uses a differential amplitude-comparison scheme. However, the DABS reply preamble requires special treatment by BCAS equipment to guard against the effects of multipath. A dynamic thresholding scheme in the DABS reply processor was found to provide greatly improved performance in processing DABS reply preambles in certain air-to-air multipath situations.

ATCRBS asynchronous interference or "fruit" was found to have little impact on the processing of DABS replies even in the dense Los Angeles airspace. As a consequence, it was found that error correction of DABS air-to-air replies is not required.

The detection of DABS squitter transmissions is accomplished without prior knowledge of the discrete address of the DABS transmission. It is thus not possible to reject invalid DABS replies on the basis of a simple parity check. When listening for squitters on the bottom antenna. BCAS receives what appear to be valid DABS preambles at relatively high rates. A scheme was devised for rejecting these false DABS replies at an early stage in the processing so that they would not tie up the DABS surveillance processor. By rejecting all replies with more than 35 low confidence bits, valid and invalid signals can be separated very effectively.

5.4 ATCRBS Surveillance

5.4.1 ATCRBS Interrogation Link

Reduction of the ATCRBS interrogation power was found to be useful in improving the reliability of the ATCRBS air-to-air link, particularly for the bottom antenna and in cases where the target is located at a significant look-down angle. The performance improvement occurs when the echo of the interrogation is reduced sufficiently so that it no longer exceeds the triggering threshold of the transponder receiver. Interrogation power programming is accomplished as a natural by-product of the whisper-shout technique which is used for controlling synchronous garble on the ATCRBS reply link.

5.4.2 ATCRBS Reply Link

Much of the development of the BCAS surveillance system was focused on improvements of the ATCRBS reply link. Several significant improvements were achieved in the design of the ATCRBS signal processor and the ATCRBS reply correlation and tracking algorithms.

The ATCRBS reply signal is inherently very susceptable to corruption by multipath reflections. It was found that the use of dynamic thresholding was effective in rejecting low-level multipath. Variable thresholds have usually been avoided in ATCRBS reply processors because they tend to discriminate against overlapping weak replies. (The processor must be able to simultaneously decode overlapping replies with reasonable success.) However, when used in conjunction with the whisper-shout technique, this disadvantage of dynamic thresholding is largely overcome, since most overlapping replies received in response to whisper-shout interrogations are of approximately equal amplitudes. It was found that very few replies were lost by the mechanism of threshold capture when dynamic thresholding is used [illegible] whisper-shout.

The whisper-shout technique achieves a significant and [illegible] improvement in the reduction of synchronous reply interference. The accuracy and reliability of ATCRBS tracks in range and altitude is noticeably improved by the use of this technique.

A number of tracker refinements were made to improve the quality, continuity, and reliability of tracks and to reduce the occurrance of false tracks. Modifications to the rules for track extension and [illegible] increased the reliability of the tracks by over 10% and reduced the incidence of false tracks by about 50:1. A geometrical algorithm was also developed to eliminate false tracks caused by specular reflections from the ocean surface. This was very successful in reducing the false track rate over water.

5.4.3 Operational Tests

A recent test series, in which a Boeing 727 carrying real-[illegible] equipment was flown to New York, Baltimore, Washington, D.C., and [illegible] gave an opportunity for gaining experience with BCAS along operational [illegible] paths. In a data base of several hours duration, the total number [illegible] alarms generated (including positive advisories, negative advisories [illegible] limit-rate advisories) was zero. Yet during this time essentially all [illegible] aircraft flying nearby were being tracked by the BCAS equipment. As many as 19 aircraft were simultaneously in track.

Case studies were performed on the tracks of interesting aircraft that passed nearby. In particular, a number of chance high-speed encounters were identified and examined in detail to estimate closing speed, traffic density, and other characteristics. In all of these high-speed encounters, BCAS tracks were established early enough to provide at least 36 seconds of warning time prior to the point of closest approach.

Additional case studies together with a statistical analysis of the data base as a whole were used to estimate the probability that a BCAS track exists for a given aircraft and the probability that the track is updated on any given one-second scan. Results of these studies indicate high levels of both probabilities, especially for the important region out to 3 nmi. Here, the probability of track is about 97% while the probability of update is 80% or higher.

Thus, although there were zero alarms during the flight, if a potentially hazardous encounter had occurred, a BCAS alarm would almost certainly have been generated.

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APPENDIX A

AMF BCAS MODIFICATIONS

During the development of BCAS the Airborne Measurements Facility was modified to add a number of DABS processing and recording operations. The original ATCRBS data acquisition capabilities were retained. Modifications included the addition of a pair of video processing and digitizer circuits, a DABS reply preamble detector, and a DABS message and confidence bit processor (see Fig. A-1).

A transmitter was built with control logic which can generate Mode 3/A, C, D or one of four DABS discrete surveillance interrogation formats. The DABS interrogations provide options for requesting either a fixed 4096 identity code or an encoding altimeter code in the surveillance reply. Also the DABS interrogations provide an ATCRBS lockout option with either type of requested reply.

During flights the MCU continuously generates one of the DABS interrogations as selected by a front panel switch. The interrogations are generated at a rate of 62/sec and transmitted alternately on the top and bottom antennas. Antenna switching between top and bottom occurs just prior to every other interrogation; interrogation time and transmitting antenna are recorded.

The DABS transponder on the target aircraft operates in a diversity mode, transmitting DABS 56 bit surveillance replies on the antenna which received the strongest interrogation preamble. If the transponder can successfully decode an interrogation, it transmits the requested reply. In order to gather link reliability data, provision was made to transmit a nine bit reply count in place of the altitude code. The count increments on every reply generated in response to a discrete interrogation. Also in all replies is a bit included only for experimental purposes to identify the antenna from which the reply was transmitted.

Along with discrete replies the transponder also independently transmits DABS All-Call replies once per second with randomly jittered timing to prevent undesireable signal synchronization. The All-Call replies, which simulate squitter replies, are transmitted alternately from top and bottom antennas. Antenna switching occurs between every All-Call reply.

The video digitizer, quantizer, DABS preamble detector and data demodulator are in accordance with FAA-ER-240-26A and (DABS ground sensor), consistent with equipment used in the real time BCAS Experimental Units.

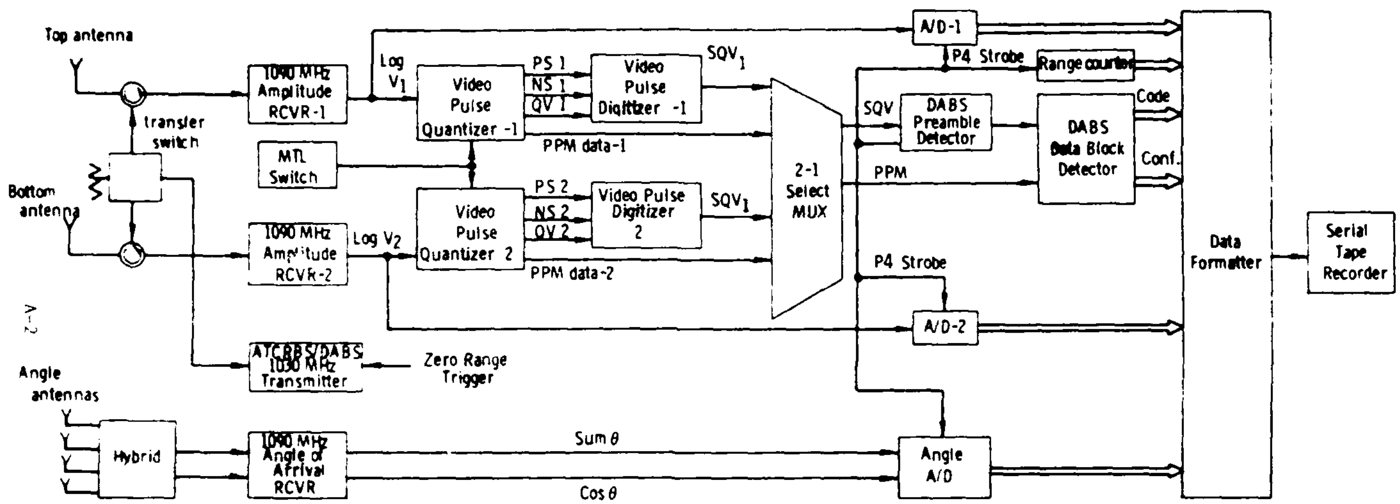

Fig. A-1. AMF DABS block diagram.

When the interrogation unit transmits an interrogation the AMF recording circuitry is not enabled until a reply preamble is detected. When a reply preamble is detected an AMF pulse data word is recorded containing pulse information (amplitude on both antennas, width, and time of arrival) based on sampling the fourth pulse of the reply preamble, P_4. The preamble detector enables the message bit processing circuitry which generates 56 bit declarations and 56 confidence bits corresponding to each bit of the DABS reply. The 112 bits of DABS reply information are recorded by the AMF immediately following the P_4 pulse data word.

At the time of the data flights. ATCRBS fruit data is also recorded by the AMF. In this case, the AMF operates in a mode in which each received pulse generates a single pulse data word, which records pulse amplitude received on top and bottom antennas, pulse width, and time of arrival. Software processes the pulses to form replies which are analyzed to obtain fruit statistics.

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